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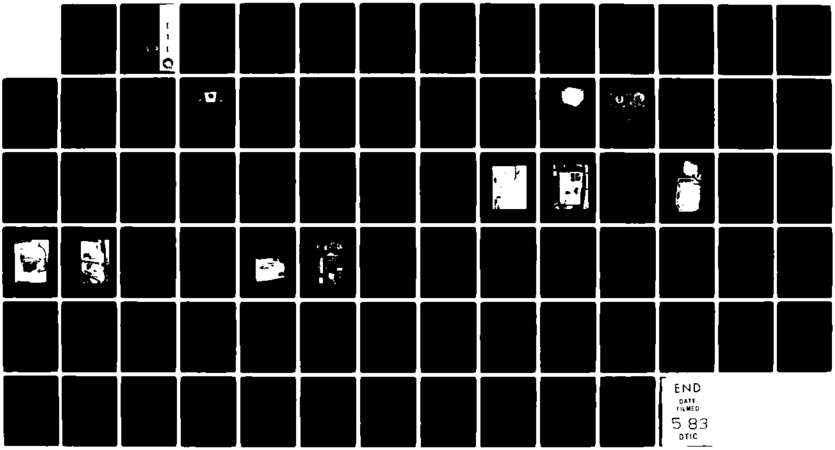

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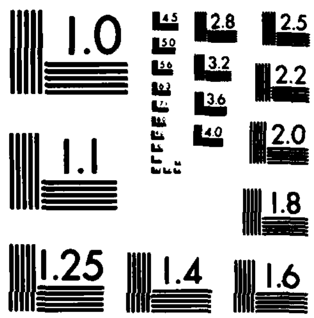

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Inertial survey applications to civil works

Edward F. Roof

JANUARY 1983

U.S. ARMY CORPS OF ENGINEERS
ENGINEER TOPOGRAPHIC LABORATORIES
FORT BELVOIR, VIRGINIA 22060

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ETL-0309	2. GOVT ACCESSION NO. AD-A127	3. RECIPIENT'S CATALOG NUMBER 508
4. TITLE (and Subtitle) INERTIAL SURVEY APPLICATIONS TO CIVIL WORKS		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) EDWARD F. ROOF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Engineer Topographic Laboratories Fort Belvoir, Virginia 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 361-31785
11. CONTROLLING OFFICE NAME AND ADDRESS Office of the Chief of Engineers DAEN-CWE-BU Washington, DC 20314		12. REPORT DATE January 1983
		13. NUMBER OF PAGES 77
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Inertial Survey Systems
Inertial Measuring Units
Reference Frames
System Modules
System Operation
System Accuracies
Operational Results

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report contains a basic explanation of inertial survey systems presently being used; Operational results in their use and an analysis of their potential use by the Corp of Engineers in support of Civil Works projects.

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PREFACE

This study was conducted under OCE Project 361-31785, Surveying Applications to Civil Works.

The study was done during 1981-1982 under the supervision of Mr. Fred Gloeckler, Jr., Chief, Precise Survey Branch; Mr. John G. Armistead, Chief, Surveying and Navigation Division; and Mr. Eugene P. Griffin, Director, Topographic Developments Laboratory. In addition, the guidance and assistance given by Mr. Ed East and Mr. M. K. Miles of OCE/Engineering Division, Civil Works Directorate, is acknowledged.

COL Edward K. Wintz, CE, was the Commander and Director and Mr. Robert P. Macchia, was Technical Director during the report preparation.

INERTIAL SURVEY APPLICATIONS TO CIVIL WORKS

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INERTIAL SURVEY APPLICATIONS TO CIVIL WORKS

I. INTRODUCTION

1. **GENERAL.** Ever since the birth of the nation, the Corps of Engineers has been very active in the fields of surveying and mapping. From the early days of exploration and the building of the nation to its present role in construction, flood control, management of the nation's navigable inland waterways and coastal harbors and its recently added responsibility to protect the ecology of the nation's wetland areas, the Corps has always included surveying and mapping efforts. The cost of these efforts has increased yearly until it has finally reached approximately $100 million per year. Even though this represents as large an investment as most other federal agencies spend in surveying and mapping, the Corps has recently fallen behind other federal agencies and the private sector in taking advantage of the most recent technologies that have entered the surveying and mapping fields. Wider applications of these recently developed technologies and development of new technologies to meet specific Corp needs can provide increased efficiency and offer significant savings for the Corps surveying and mapping programs.

2. **BACKGROUND.** In April 1979, the Chief, Engineering Division, Directorate of Civil Works, Office of the Chief of Engineers, formed an OCE team to examine the surveying requirements and activities of the Lower Mississippi Valley Division (LMVD). The objectives of the OCE team were to:

Identify the types of surveying being accomplished.
Identify the mission requirements that controlled the type of surveying being accomplished.
Identify the dollar costs and workforce requirements to accomplish the survey work.
Identify the survey work by in-house and contract work force.
Identify past trends and future expectations with regard to requirements and resource allocations.
Identify any technical, management or administrative problems in accomplishing these activities.

Meetings were conducted by the OCE team at LMVD in Vicksburg, Mississippi and New Orleans, Louisiana. During these meetings it became clear to the OCE team that many of the Corps projects in surveying and mapping, both in-house and contract, were not necessarily being accomplished in the most efficient and cost effective manner.

After obtaining additional data from other districts and examining some of the new technologies developed for surveying and mapping purposes, OCE tasked the United States Army Engineer Topographic Laboratories (USAETL) to prepare a report on the potential use of the recently developed inertial survey technology in accomplishing various surveying and mapping projects.

3. **SUMMARY.** Inertial navigation systems are devices which implement Newton's laws of motion to solve navigation problems. The heart of an inertial navigation system consists of a precise inertial platform with gyroscopes keeping its three orthogonal axes oriented in space. Each axis contains an accelerometer that measures the acceleration in that axis' direction. The accelerometers outputs are processed into digital form and input into a computer for integration into distance traveled. The distances traveled in the X, Y, and Z directions are then applied to known X, Y, and Z coordinates of the beginning point to compute the position of the system at any time.

The accuracy of inertial survey systems is dependent on system component errors, system mechanization errors, operator induced errors, environmental induced errors, and basic horizontal and vertical control station errors. As with conventional surveying instruments, different operational techniques and procedures produce different accuracy results. Horizontal accuracies can range from 10 to 25 centimeters (0.33-0.82 feet) and vertical accuracies can range from 1 to 12 centimeters (0.03-0.39 feet). Standards of accuracy, in terms of NGS standard classifications, i.e., 1st, 2nd or 3rd order, have not been fully developed compared to conventional surveying methods. If the surveyed area is of sufficient size and points properly spaced, 2nd order, class II horizontal accuracy (1 part in 20,000) can be expected. Although the inertial system is more accurate from an absolute standpoint in the vertical direction, it is very difficult for it to produce results equal to conventional surveying methods using differential leveling. The vertical proportional accuracies are dependent upon the horizontal distances between points. Third order (1.2 cm times the square root of the distance in kilometers) vertical is about the best that can be expected with an inertial system.

At present, three companies manufacture inertial navigation systems for use in geodetic and lower order control surveying. All were originally designed for military purposes. These systems are: The Auto-Surveyor of Litton, Inc., originally designed as the Position and Azimuth Determining System (PADS) for the US Army Artillery; the GEO-SPIN of Honeywell, Inc., a modified version of the inertial navigation system being built for installation in the US Air Force's B-52 bombers; and the FILS (Ferranti Inertial Land Surveyor) of Ferranti, Inc., originally designed as the British Army verision of the PADS.

Other Government agencies and the private sector have been using inertial technology to accomplish many of their geodetic and lower order control surveying projects. These include other US Army elements, Defense Mapping Agency, Bureau of Land Management, Canadian Department of Energy, Mines and Resources, and Span, International, Inc. All report sizeable time and dollar savings resulting from their use of inertial surveying systems.

The Civil Works side of the Corps has used inertial surveying systems for several demonstration projects. Corps users report mixed opinions of the accuracy results, but most report time and dollar savings.

An examination of survey work in some of the districts indicates that the Corps may realize substantial time and cost savings with the use of inertial survey systems to accomplish some of their work. With proper consolidation of control requirements and careful planning within districts and between districts significant savings can be realized. An additional benefit obtained by using inertial technology is better utilization of limited personnel resources.

For the immediate future (next 2-4 years), it appears that greater use of the private sector's inertial survey capabilities should be considered where job requirements and economics permit. For the more distant future, the purchase of one or two systems should be seriously considered by the Corps. Cost in 1981 dollars would be $1.2 - 1.5 million for the first system, including needed spare parts and some training for operators, as well as training for minor troubleshooting. Each additional system would cost $0.5 million.

Studies should be immediately conducted to determine the specific type and location of work for which inertial systems should be used.

II. THE BASIC PRINCIPLES OF INERTIAL NAVIGATION

1. LAWS OF INERTIA

Inertial navigation systems are devices that implement Newton's laws of motion to solve the navigation problem. Newton's laws of motion are stated as follows:

a. Every body continues in its state of rest, or uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it.

b. The change of motion is proportional to the motive force impressed; and is made in the direction of the straight line in which that force is impressed.

c. To every action, there is always opposed an equal reaction.

The first law indicates the inert character of matter. The measure of this resistance, to change in motion or direction, is mass. The second law gives the relationship between force, mass, and acceleration in the well-known equation $F = ma$. The third law points out that the body being acted upon, also exerts a force against the body producing the force. The above laws have equivalents in rotational terms. A body in rotation will tend to continue rotating at the same angular rate and to maintain the same axis of rotation in space until some force is exerted on it.

It should also be noted that Newton's laws of motion are postulated with the assumption that the observations are taken with respect to a frame of reference that is fixed in space. It has been proven that a body can be at rest or in uniform motion in a straight line in one frame of reference and be traveling in a curve and accelerating with respect to another frame of reference. When Newton's laws of motion hold in one frame of reference, they also hold in any other frame of reference which is moving at constant velocity relative to the original frame of reference.

2. **GYROSCOPES.** A gyroscope is most simply thought of as a rapidly spinning rotor supported on a ball and socket mount which allows freedom of tilt of the spin axis relative to the base in addition to spin freedom. When such a device is initially set with the spin axis pointed in some direction in space, (toward a certain star) the spin axis preserves this direction with a high degree of fixity.

A rapidly spinning rotor imparts three unique properties to a gyroscope.

a. It makes the rotor and rotor shaft rigid against angular deflections.

b. If a torque is applied about an axis transverse to the spin axis, the rotor turns about a third axis at right angles to the others.

c. When the torque is removed, the rotation of the axis ceases.

A distinguishing feature of any gyroscope is its accuracy in maintaining either its original orientation in inertial space, or to measure an angular rate correctly. A perfect gyro would maintain its spatial direction forever (supposing no mechanical failure) and measurements made with respect to the indicated direction would be as accurate as the auxiliary equipment. However, gyroscopes do drift away from their reference direction. Measurements made with respect to the indicated direction are in error by at least the angular drift of the gyro. A good gyro will drift at an extremely low rate so that measurement accuracy will be good over a reasonably long period of time.

Starting with the concept of a rapidly spinning rotor in inertial space, the basic functional design of a gyro may be accomplished in the following five steps:

a. Have a rapidly spinning rotor on an axle.

b. Mount the axle in a gimbal set having one or two degrees of freedom with respect to the gyroscope housing.

c. Provide suitable means for restraining the angular motion or precession of the axle, thereby shaping the transient and steady state response of the gyro to inputs of angular rate or torque.

d. Provide a means (pickoff device) for measuring the motion of the external housing relative to the axle.

e. Furnish a means (caging device) for initially setting the axle to a desired attitude or position, subsequently causing it to move in an ordered precession.

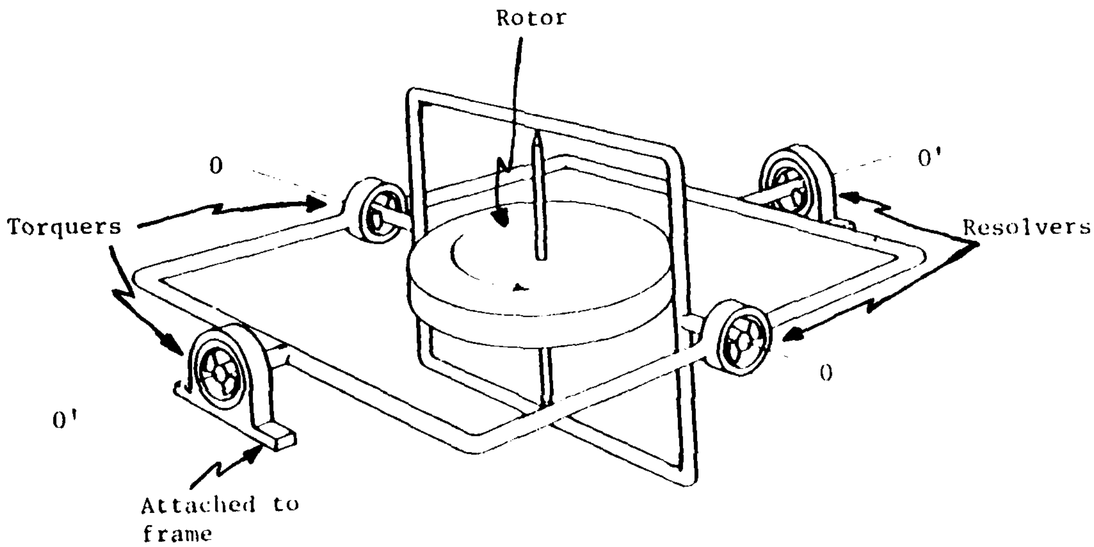

Figure 1. Diagram of a Two-degree of Freedom Gyroscope

Only two axes gyroscopes will be described since they are the type primarily used in inertial survey systems. A two-degree-of-freedom gyro can be used to control angular velocity around two orthogonal axes. Figure 1 is a line schematic diagram of a two-degree-of-freedom gyroscope. The inner gimbal axis is 0'0' and the outer gimbal is 00. The two gimbal axes allow the case to be tilted about axis 0'0' or axis 00 without disturbing the space alignment of the rotor spin axis.

Tilts represent an angular disturbance to whatever the gyroscope is attached and are detected by the resolvers that send out error signals to a computer, which sends a message to a servo system to remove the disturbance tilt. The torque generators shown in Figure 1 use data from a computer so that the gyro can be torqued to the desired orientation.

The two basic gyroscopes used in present day inertial survey systems are a floated, two-degree of freedom, gas lubricated spin-bearing gyro and a two-degree-of-freedom, electrically suspended gyro.

The floated gyroscope is based on mounting the gyro gimbal in a fluid of the same average density. This means that the fluid, instead of the gimbal bearings supports the gyro assembly, thereby reducing gimbal friction to extremely low levels. The gyro rotor wheel is driven at a high constant rate of speed (about 24,000 RPM) by a synchronous motor. Usually the gyro motor is inside out with the rotor outside the stator to develop the largest possible angular momentum consistent with requirements for weight and size. Instead of ball bearings, these gyros now use hydrodynamic gas bearings resulting in a significant reduction in the gyro drift rate.

The electrostatic gyroscope is based on the spinning element (rotor) being a hollow sphere supported electrostatically. The hollow rotor is the only moving part of the electrostatic gyroscope. The rotor is suspended in an evacuated cavity (pressure about 3×10^{-8}mm Hg) to minimize viscous drag on the spinning rotor. After initial suspension, the rotor is brought up to speed by a rotating magnetic field produced by spin coils located around the equator of the rotor (see Figure 2). When operating speed (about 40,000 RPM) has been reached, a damping coil is energized to damp rotor nutation. There are optical pickoffs that observe readout patterns scribed on the rotor surface. This readout pattern makes the spin axis visible so that its position relative to the cavity can be determined. Electrostatic gyros have extremely low drift rates.

For a greater in depth treatment of the theory and use of gyroscopes, refer to the list of references in this report.

3. **ACCELEROMETERS.** Inertial navigation is dependent upon the measurement and double integration of change in acceleration outputs to succesfully accomplish the function of determining three dimensional positions (three accelerometers mounted orthogonally are used to accomplish this). It is the function of accelerometers to provide the measurement of acceleration. An accelerometer is a precision instrument containing a mass that is coupled to a case through an elastic or an electromagnetic restraint. It must be emphasized that the accelerometer is

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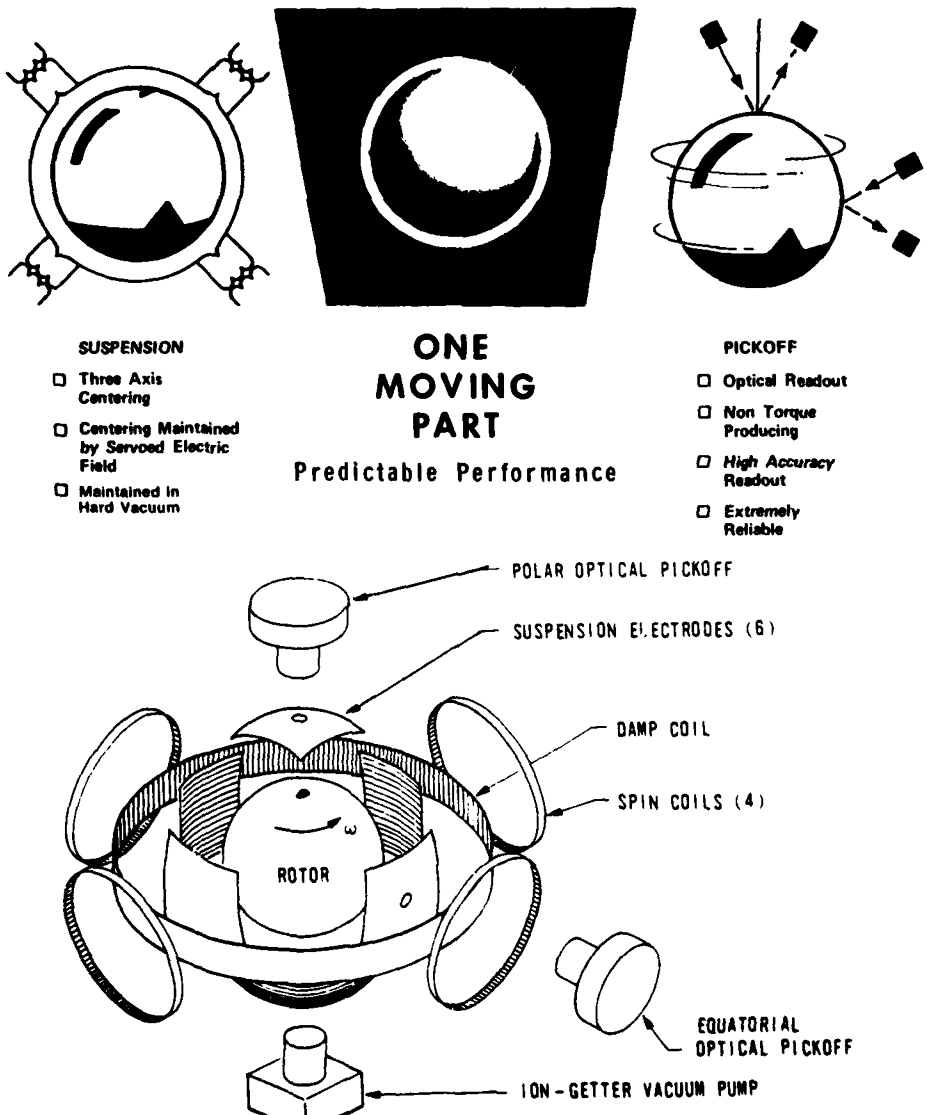


Figure 2. Pictorial Diagram of an Electrostatic Gyroscope

actually a sensor of a specific force which is the resultant of gravitational force (consisting of both mass-attraction and centrifugal effects) and inertial reaction force.

For an accelerometer to be useful in navigation, the acceleration of gravity must be compensated. The horizontal (north and east) channels are compensated by a feedback system that keeps them level or by the computation of gravity that is used to compensate the accelerometer outputs. The vertical channel (elevation) is more difficult to compensate for the effects of gravity (compensation described later in this chapter).

There are a variety of precise accelerometers but only the hinged pendulum, torque-to-balance type of accelerometer will be described since these are the types of accelerometers presently used in inertial navigation systems for geodetic surveying. Accelerations along the sensitive axis produce torques that induce rotary motion of the pendulum. These rotations are detected by a signal generator that converts them to an electrical signal and transmits this signal to an amplifier, or pulse rebalancing electronics which drive torquers to maintain the pendulous mass at a null position. The amount of current used by the torquers, or the pulses needed to maintain the accelerometer at its null position are a measure of the acceleration being sensed. A diagram of a hinged pendulum, torque-to-balance accelerometer is shown in Figure 3.

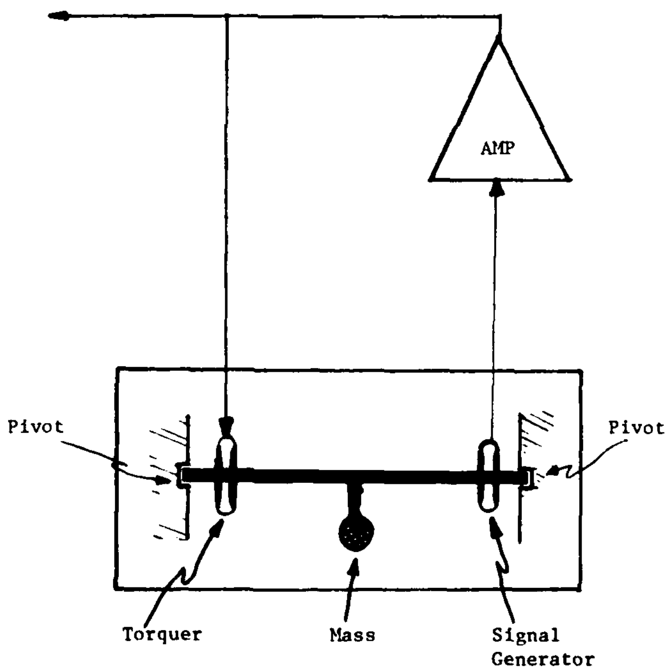


Figure 3. Diagram of a Hinged Pendulum, Torque-to-Balance Accelerometer

The basic operations of an accelerometer triad can best be explained by the use of a vector diagram (See Figure 4). At t = 0, the accelerometer triad was located at point 0 in Figure 4. Some time later at t+ the accelerometer was located at point P. Looking at Figure 4 and making the assumption that the accelerometers sensitive axes are exactly in alignment with the N-S, E-W, and the plumb line as well as having no error in scale factor, we can see that the accelerometer with the sensitive axis on line O-Y has measured only the change of latitude along the N-S line. The accelerometer with the sensitive axis on line O-X has measured only the change in longitude along the E-W line. The accelerometer with the sensitive axis on line O-Z has measured only the change of elevation.

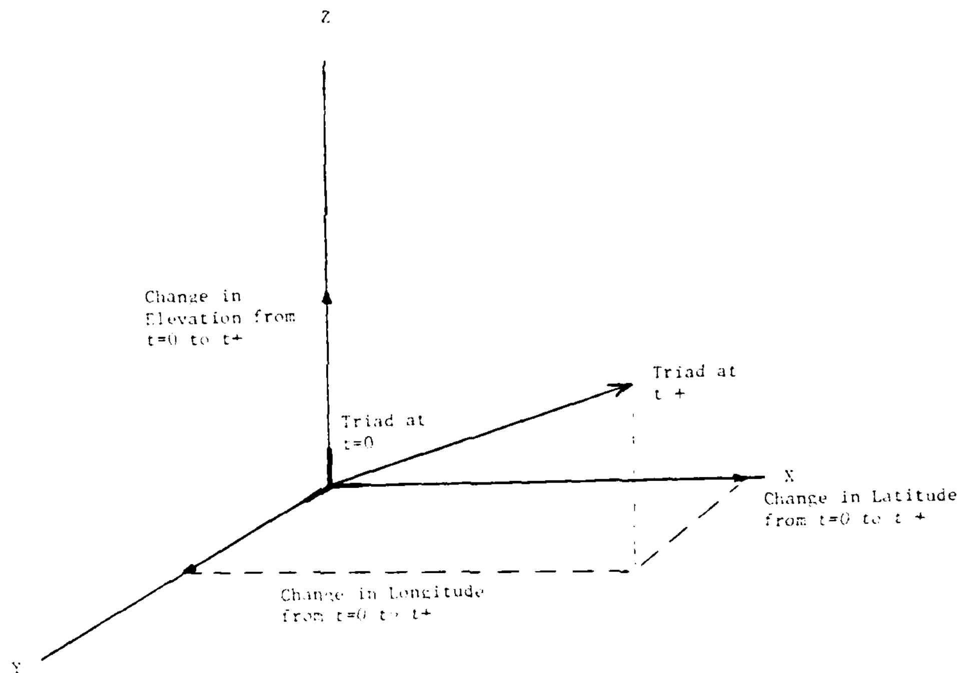


Figure 4. Vector Diagram of Accelerometer Triad

There are various error sources that effect the performance of accelerometers. The magnitude of most of these errors is determined during a premission calibration routine and is then compensated for during operational use. However, two errors sources for the local level, north-oriented inertial systems are best determined by operating the system over a precise calibration course. The two error sources are: (1) the accelerometer scale factor, and (2) accelerometer misalignment. Calibrating for accelerometer scale factor is analogous to calibrating a steel tape or an electronic distance meter and is fairly easy to accomplish. Accelerometer misalignment errors are more difficult to detect and eliminate. Misalignment errors are caused by procedures in mounting accelerometers on the platform, random changes in gyroscope and platform drift, changing gravity vector during an operational mission, and unknown deflections of the vertical at the starting and terminal stations. All of the above error sources cause what can be termed "a cross-coupling error". Figure 5 shows two accelerometers. The top diagram shows an accelerometer with its sensitive axis exactly perpendicular to a north-south line, which is the line along which the accelerometer is moving. The bottom diagram shows an accelerometer with its sensitive axis misaligned 10 arc seconds from being perpendicular to a north-south line, which is the line of travel along which the accelerometer is moving. For the perfectly aligned accelerometer, no acceleration had been measured, therefore no change in position is computed from the output. For the accelerometer that is misaligned by 10 arc seconds, an apparent acceleration was seen. This apparent acceleration, integrated twice, converts into an error in easting or longitude by the amount of distance that the unit traveled in the northerly direction times the sine of the misalignment angle. If the north distance that the unit traveled was 15,000, feet then the error in the easting or longitude would be (15,000) x (0.00004848), which results in an error of 0.727 feet for the longitude.

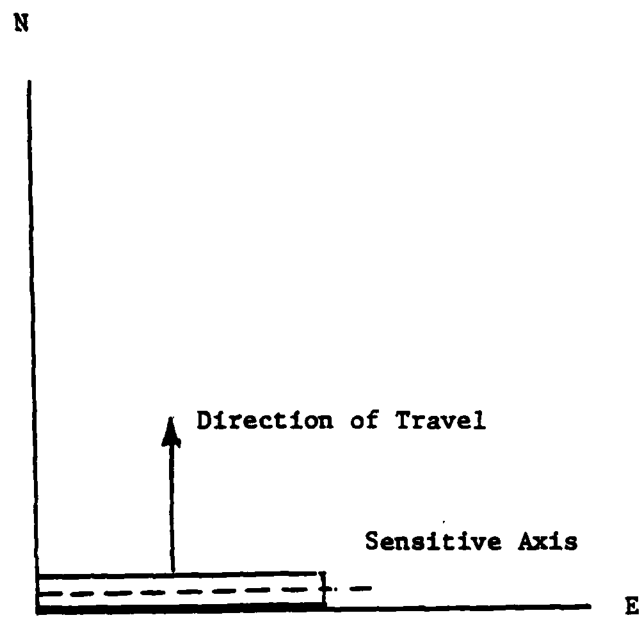
For a more detailed discussion of accelerometers, refer to the list of references in this report.

4. INERTIAL MEASURING UNIT (IMU). The IMU is the heart of the inertial navigation system. It is defined as the stable platform with its support electronics. For the purposes of this report, the heart of the IMU is a cluster of three accelerometers and two two-degree of freedom gyroscopes properly mounted on a stable platform. The stable platform is isolated from the maneuvering of the vehicle in which it is carried by the gimbals which allow the case of the IMU full freedom of motion about the stable element.

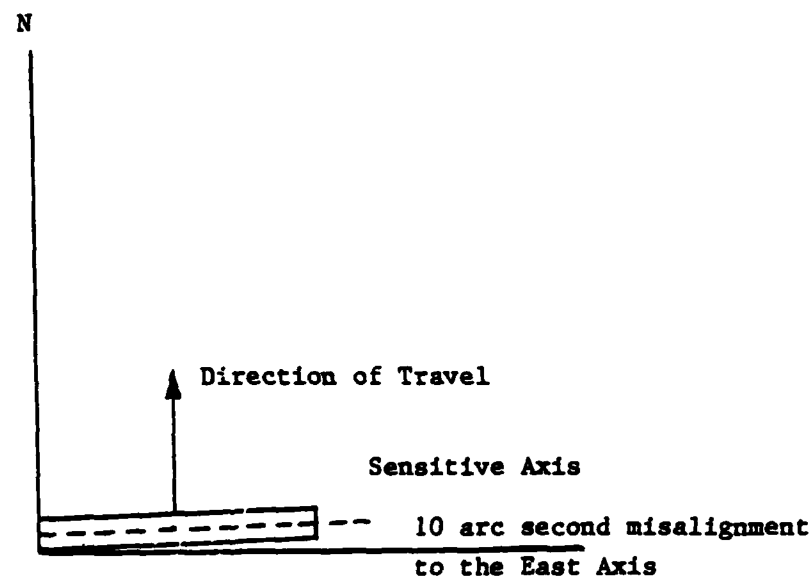
The gyroscopes are mounted on the stable platform in such a manner that full platform stabilization is provided. This means that the gyroscopes will be mounted on the platform orthogonally. Since two-degree-of-freedom gyroscopes are used, one gyroscope is used to control the X and Z axis and the other gyroscope is used to control the Y and Z axes. The Z axis of the YZ gyroscope is usually slaved to the Z axis of the XZ gyroscope, but other methods of using the information from this redundant axis are sometimes employed.

The accelerometers are mounted on the stable element so that the sensitive axis of the accelerometers form an orthogonal system in which acceleration can be measured. Figure 6 shows a four-gimbal stable element using two two-degree-of-freedom gyroscopes and three accelerometers.

As stated previously, the stable element is mounted in gimbals to isolate it from its case and the vehicle in which the system is being carried. The first or innermost gimbal contains the stable element. The axis that it rotates about is usually vertical. This gimbal is called the azimuth gimbal. The axis of the azimuth gimbal is mounted in a second gimbal which is called the inner roll gimbal. The axis of the inner roll gimbal is mounted in a third gimbal, which is called the pitch gimbal. The axis of the pitch gimbal is mounted in a fourth gimbal called the outer roll gimbal. The outer roll axis is mounted to a frame.



a. Sensitive axis parallel to the East Direction



b. Sensitive axis misaligned

Figure 5. Accelerometer Alignment

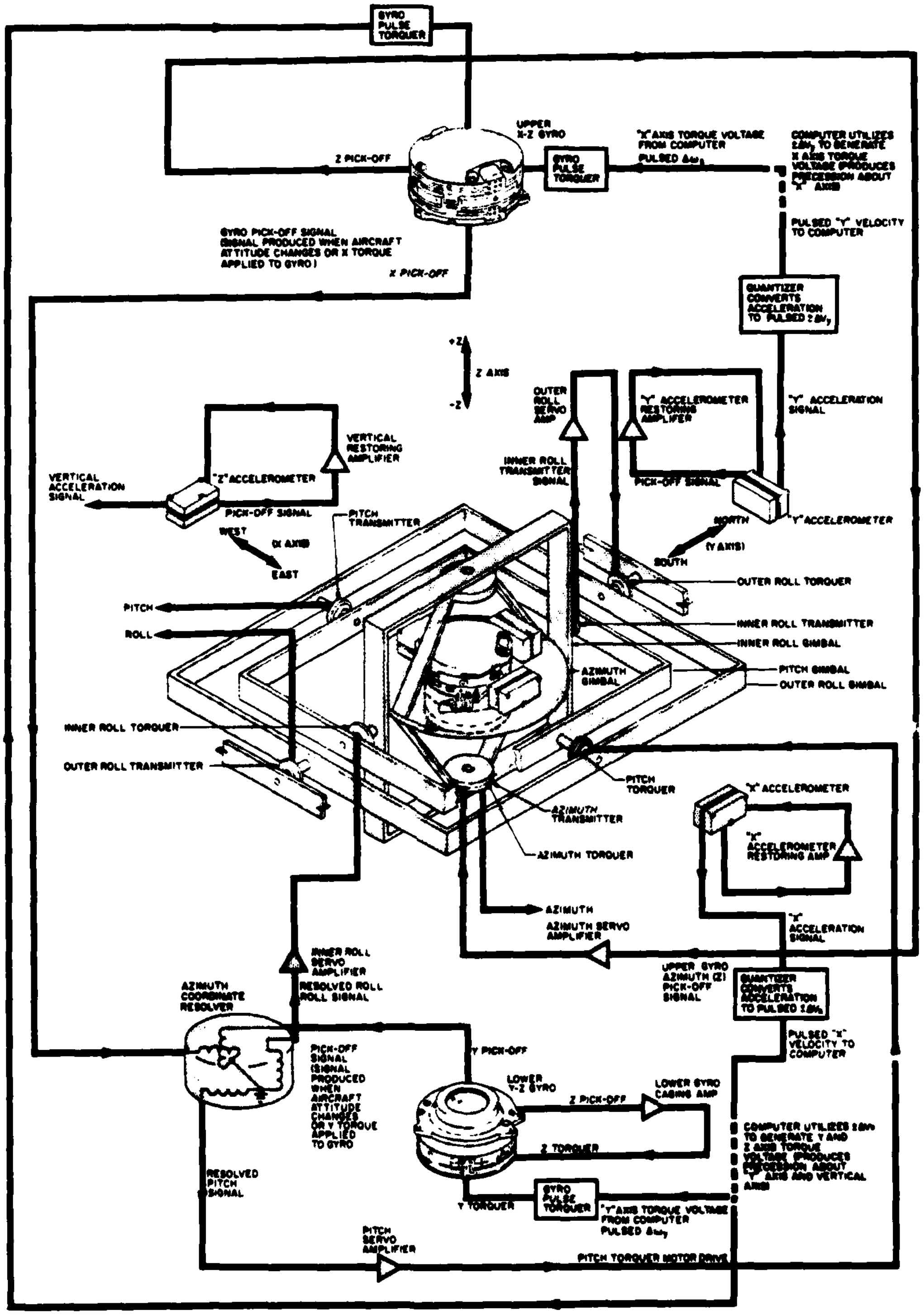


Figure 6. Stable Element (4 gimballed) Diagram

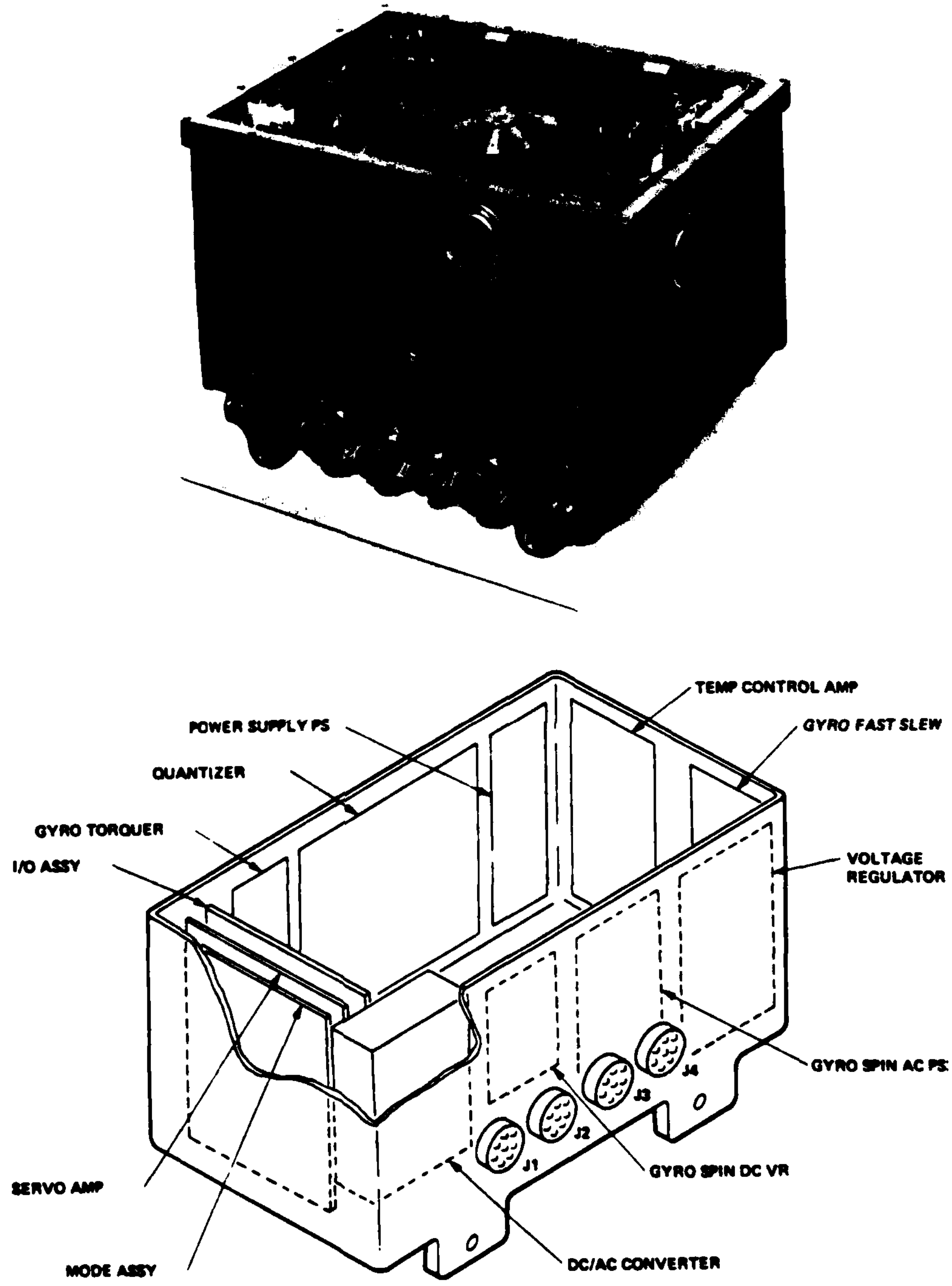


Figure 7. Litton IMU

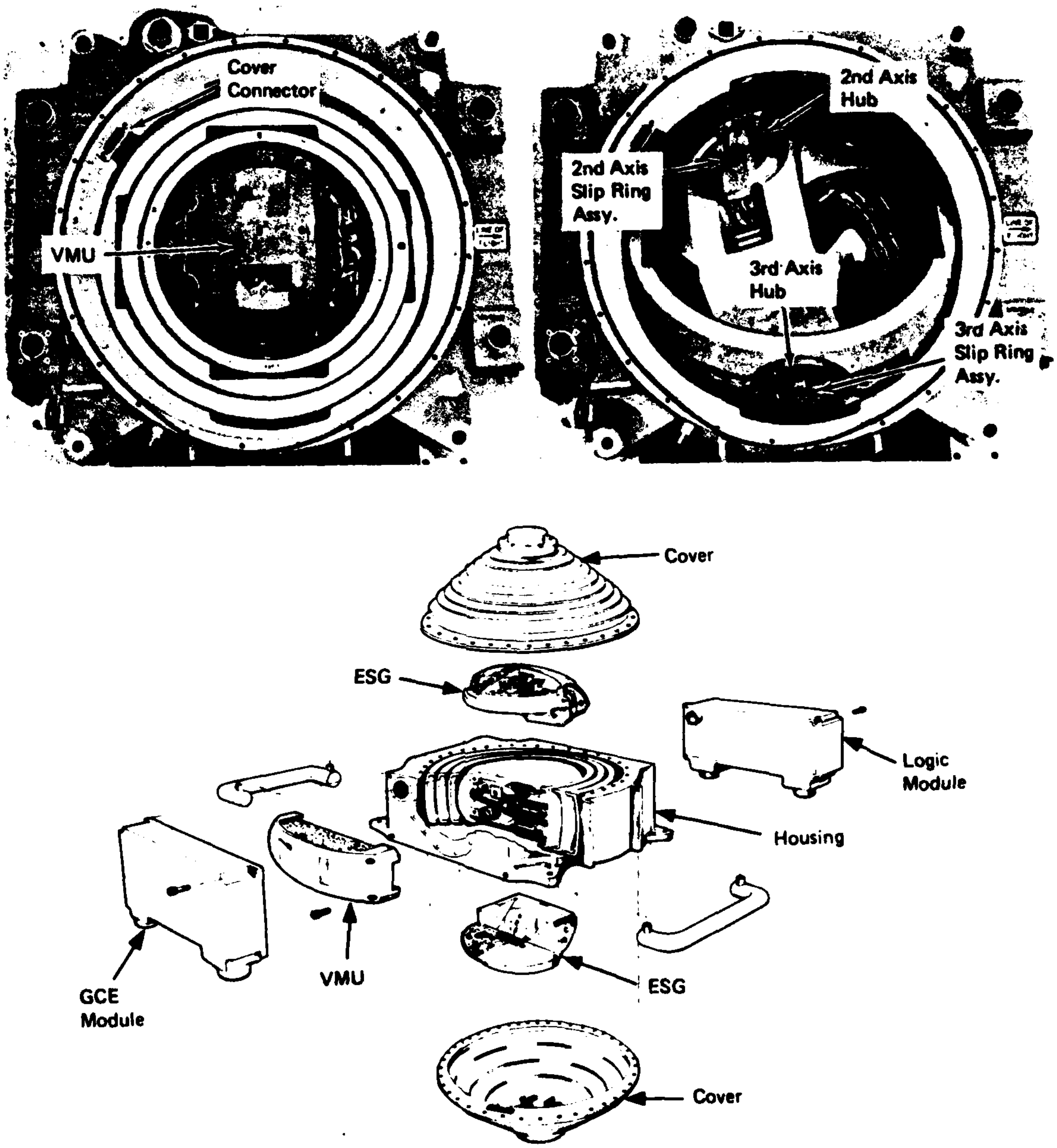


Figure 8. Honeywell IMU

Three gimbals are sufficient to provide isolation for the stable element. However, if the system rolls 90 degrees about the second gimbal axis, the third axis becomes aligned with the first axis and the stable element is no longer free to rotate about the third axis. This condition is called gimbal lock and the fourth gimbal (outer roll) is added to the system to insure isolation of the system regardless of vehicle attitude.

The axes of all gimbals are equipped with torquers at one end and resolvers at the other end. The torquers are servo motors that can be used to control the attitude of the gimbals. The resolvers are electromechanical components for the purpose of measuring the angle of gimbal rotation. The azimuth resolvers in inertial systems used for surveying are usually of higher accuracy than the resolvers used on the other gimbal axes.

Inertial measuring units also contain considerable electronics. The electronics perform various functions such as controlling the servos on the various gimbals, providing the proper power to various parts of the IMU, translating the information from the gyroscopes and accelerometers for computer use, translating commands from the computer for use in the IMU and providing proper operating temperatures within the IMU. The IMUs used by Litton and Honeywell for inertial surveying are shown in Figures 7 and 8.

For a more detailed discussion of inertial measuring units refer to the list of references in this report.

5. REFERENCE FRAMES: The reference system for which Newton's laws of inertia are valid is called an inertial reference system and can be defined as a system that maintains a fixed attitude (unaccelerated) with respect to the stars. To navigate or locate a position on the earth, it is desirable to use a rotating reference frame. To translate from one reference frame to another, it is necessary to examine how they are used for inertial navigation.

When utilizing inertial navigation systems near the earth's surface, it is preferable to use a non-rotating, earth-centered inertial reference frame with one of the orthogonal axis parallel to the earth's axis of rotation. (See Figure 9).

The surface on which geodetic surveying and terrestrial navigation computations are based is an ellipsoid, which approximates the earth with the axis of rotation of the earth being the minor axis of the ellipsoid. This frame is called the geodetic reference frame and has its orthogonal axes aligned with the north, east and elevation on a plane tangent to the ellipsoid at the point of interest. In the interest of practicality and because of the limits of the resolution of the inertial components presently used, the elevation direction of the geodetic reference frame used by an inertial system is considered to be normal to the reference ellipsoid. In actuality, the elevation direction of the geodetic frame is normal to the geoid, which is that equipotential surface (due to the irregular gravitational field) of the earth's attraction and rotation that on average coincides with mean sea level in the open sea. (Figure 10).

It should be obvious at this point that the geodetic reference frame being tied to a rotating earth requires that data obtained from an inertial navigation system be mathematically translated and rotated from the inertial reference frame to the geodetic reference frame or that the platform be constantly torqued to keep the accelerometers properly aligned to the north, to the east, and perpendicular to the geoid.

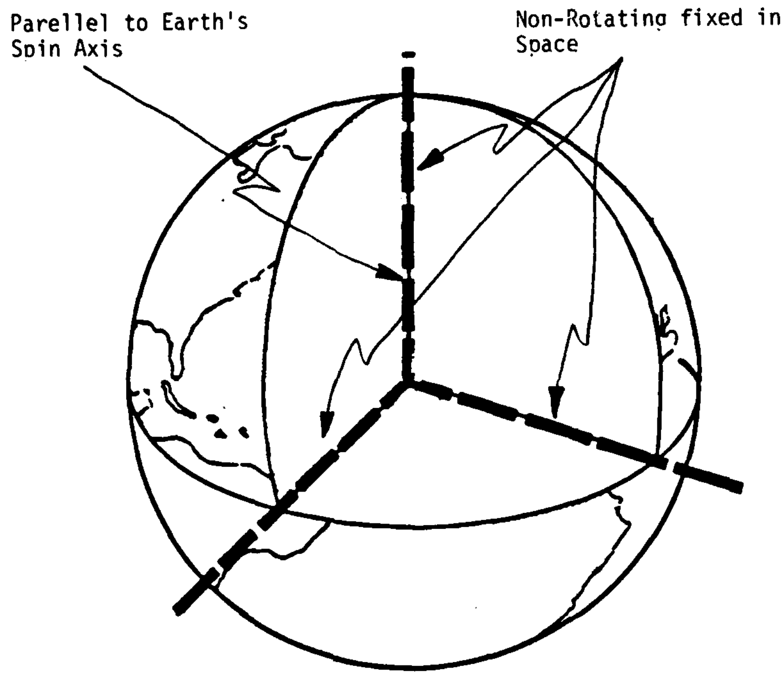


Figure 9. Inertial Reference Frame

Inertial navigation systems have been designed and fabricated in various configurations. The configuration of the system is dependent on the reference system used to obtain the basic data output. The two types of systems presently being used for geodetic surveying purposes will be described.

The first system to be described is the space-stable inertial navigation system (See Figure 11a). In the space-stable system the three accelerometers form an orthogonal triad that is oriented with the sensitive axis of the Z accelerometer parallel to the earth's axis rotation, and the X and Y accelerometers parallel to the equatorial plane with the sensitive axis of the Y accelerometer on the local meridian and the sensitive axis of the X accelerometer pointing east. The accelerometer triad remains in this inertial, non-rotating reference frame with the output of the accelerometers being mathematically rotated and translated from the inertial reference frame to the local geodetic frame.

The second system to be described is the local-level, north-oriented system (See Figure 11b). In this system the three accelerometers form an orthogonal triad that is oriented to the local geodetic frame. The sensitive axis of the Z accelerometer is oriented to the plumb line of the geoid with the sensitive axis of the Y accelerometer oriented along the local meridian (north-south) and the sensitive axis of the X accelerometer pointing along the local parallel (east-west). The platform containing the accelerometer triad is continouously torqued to compensate for the rotation of the earth and vehicle movement. This continuous torquing keeps the sensitive axes of the accelerometer triad properly oriented to the local geodetic frame (north-south, east-west and the plumb line).

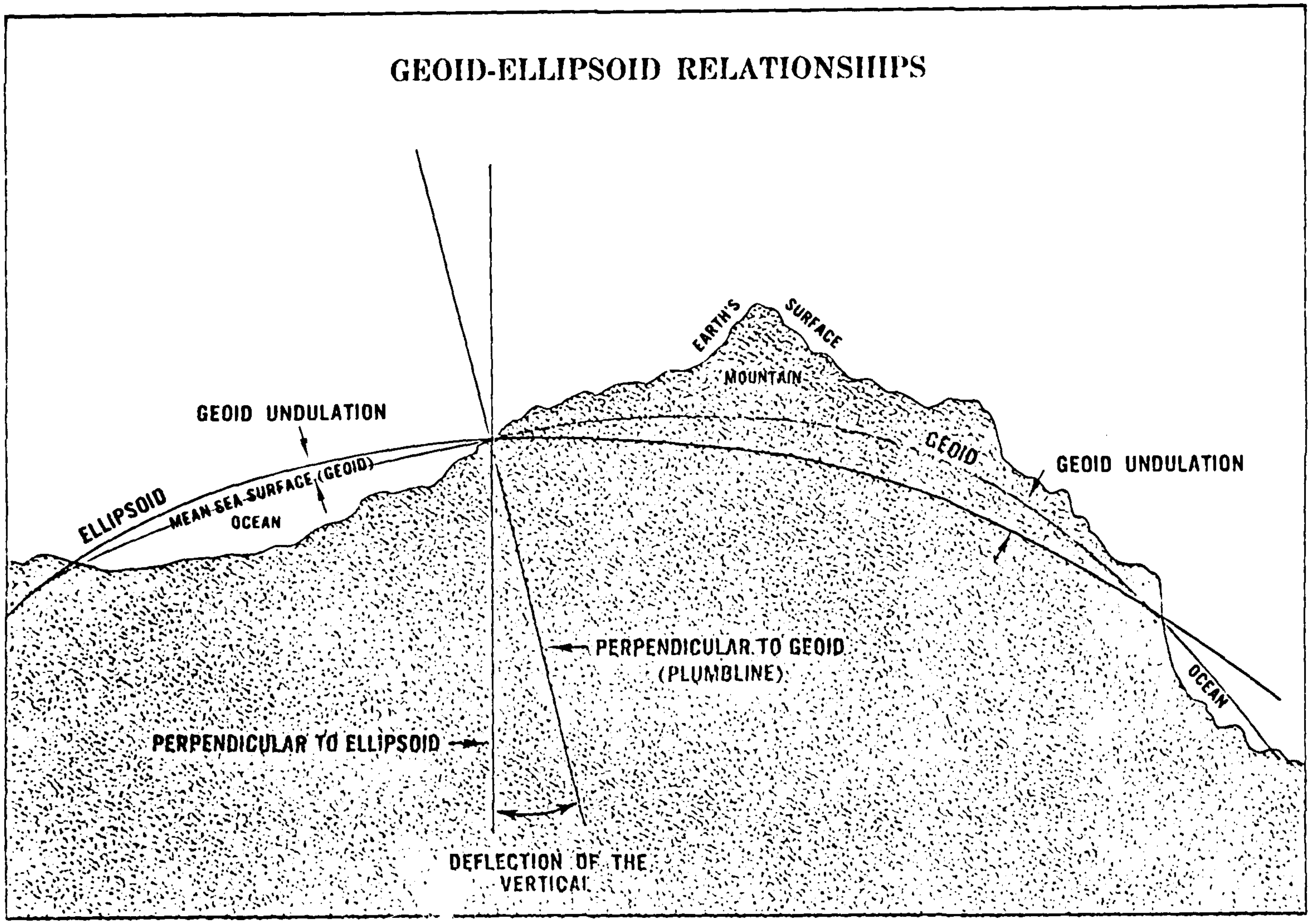


Figure 10. Geoid Ellipsoid Relationship

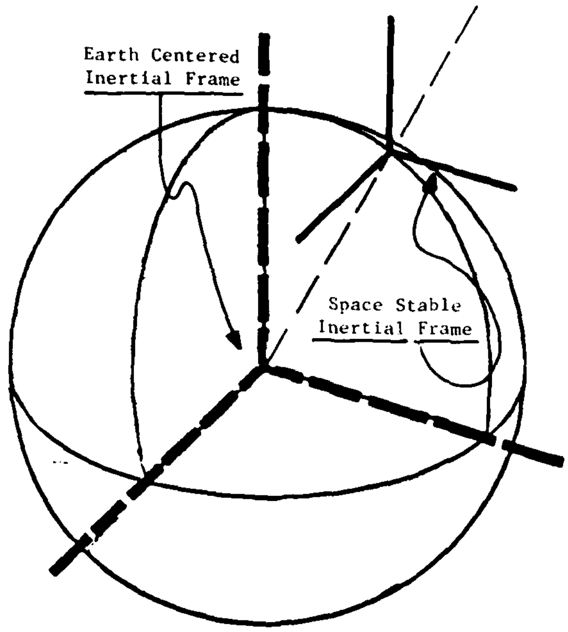


Figure 11a. Space-stable Inertial Reference Frame

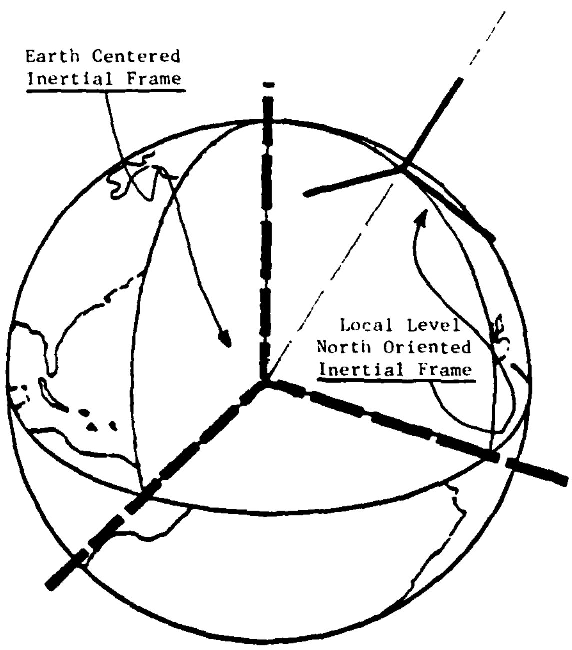


Figure 11b. Local-level, North-oriented Inertial Reference Frame

III. INERTIAL SURVEYING SYSTEMS

1. **GENERAL.** At the present time three companies have manufactured inertial navigation systems for use in geodetic surveying. In addition, the Charles Stark Draper Laboratory is building an airborne inertial surveying system with laser tracker and altimeter for use as an Aerial Profiling Terrain System (APTS). All of the systems except the APTS were originally designed for military purposes. These systems are the Auto-Surveyor of the Guidance and Control Systems Division, Litton, Inc., and was originally designed as the Position and Azimuth Determining System (PADS) for the Artillery of the United States Army. The GEO-SPIN of the Avionics Division of Honeywell, Inc., which was modified from the SPN/GEANS to be installed in the United States Air Force B-52 bombers. The third system is the Ferranti Inertial Land Surveyor (FILS) of Ferranti, Inc., which was originally designed as the British Army version of the PADS.

2. **SYSTEM MODULES.** All of the systems basically have the following major subsystems: (1) Power Supply Unit (PSU) that provides all of the operating power to the system. The input power to the PSU is usually 24-28 volts (DC) generated by the vehicles electrical system, or an auxiliary system operated from the carrying vehicle's engine. (2) Inertial Measuring Unit (IMU) with support electronics that process the output of the platform sensors into the proper digital format for use by a digital computer and process the computer output into usable signals for platform control purposes. (3) The computer or Data Processing Unit (DPU) that contains sufficient memory to store the required program to complete a survey mission as well as controlling the platform. A precise clock is part of the DPU. (4) The Data Storage Unit (DSU) can be memory in the DPU or a magnetic tape system that can be used for storing mission data for later processing. The DSU is also used to load and extract programs and calibration data into and out of the DPU. (5) The Control and Display Unit (CDU) allows the operator to interface with the system by inputting and extracting data, to receive a visual display of various data and to monitor the status of the system.

3. **SYSTEMS OPERATION.** The operation of an inertial navigation system for geodetic survey purposes can be divided into three main sub-groups. These subgroups are: (1) Premission Calibration, (2) Survey Mode, and (3) Smoothing Mode or Post Mission Adjustment.

3a. **PREMISSION CALIBRATION.** Since there is a difference in the premission calibration of the local-level, north-oriented inertial system and the space-stable inertial system, the premission calibration that is performed automatically under computer control of both systems will be described.

The premission calibration and orientation of a local-level, north-oriented inertial system begins after the power is applied to the system and the position, elevation and time have been entered into the CDU. When the power is applied to the system, the gimbals are caged (aligned) to the attitude of the IMU case. The platform containing the accelerometers and the gyroscopes is leveled to the gravity field by use of the horizontal (X and Y) accelerometers. The platform containing the accelerometers is torqued until the output of the horizontal accelerometers read zero (analogous to leveling a transit or theodolite). This places the Z accelerometer vertical with its sensitive axis along the plumb line. The platform is then oriented to its proper azimuth (sensitive axis of the Y accelerometer pointing north-south and the X accelerometer pointing east-west) by a technique known as gyrocompassing. The gyroscope designated as the X and Z gyroscope (the gyro axes east-west and vertical) is used to perform this function. This gyroscope, because of its alignment, senses earth rate (rotation) if the input axis (east-west axis) is not exactly perpendicular to the north-south line. When the gyroscope senses a component of earth rate, a command is given by the computer for the platform to turn in azimuth until the component of earth rate being sensed is reduced to zero. While the platform is being oriented in azimuth and leveled to the gravity field, an internal calibration is also being performed. During this calibration, the gyroscope and accelerometer biases, as well as gyroscope drift rates are estimated. These parameters are held fixed until the next premission calibration is performed. The calibration parameters are used during the mission for predicting platform performance during the survey. When the premission calibration and orientation is completed, the system automatically goes into the survey mode.

The premission calibration and orientation of the space-stable inertial system begins after the power has been applied to the system and the position, elevation and time have been entered into the CDU. At this time the calibration phase starts. During calibration, the gimbal resolver errors, the accelerometer scale factor, the misalignment angles and the biases are computed by torquing the platform to each of 21 prestored test positions where the output of each accelerometer and the average gimbal angle for each of the four gimbals is determined. In addition to the above parameters, the platform and gyroscope drifts are also determined. Upon completion of the calibration, the platform then aligns itself so that the sensitive axes of the accelerometer triad are parallel to the earth-centered inertial reference frame. This is accomplished by going first through a coarse alignment where the sensitive axis of the Z accelerometer is placed parallel to the earth's polar axis. Next, the X accelerometer is placed with its sensitive axis parallel to the intersection of the local latitude plane (which is parallel to the equatorial plane) and the local meridian plane, pointing outward from the earth's rotational axis. The Y accelerometer is in the local latitude plane, orthogonal to the other two accelerometers, and initially pointing east. When the coarse alignment is finished, the system goes through a fine alignment. When the fine alignment is completed, the system automatically goes into the survey mode.

3b. **SURVEY MODE.** The survey mode for both the local-level north-oriented and the space-stable inertial systems is performed in the same manner. When the premission calibration and orientation is completed and the inertial system enters the survey mode, traversing to establish geodetic control can be performed. The traverse is started by initializing the system over a control station with known values. To start the traverse, a station ID number, coordinate values (position, elevation and offset values) are entered into the CDU.

Following completion of the initial update, the system is driven to other points where geodetic parameters are required. While in transit from one point to another, the system is continuously determining its change in position. When performing a survey mission, the vehicle must be stopped every 2 to 5 minutes to perform zero velocity updates (ZUPTS) for the purpose of controlling the error growth of the system. The greater the accuracy required in determining the geodetic parameters, the closer together the ZUPTS must be performed.

ZUPTS are used by the system to provide external information to the error control system used (Kalman Filtering is the error control technique used by Litton and will be explained in the next paragraph). At the time the ZUPT is being performed, the accelerometer output should read zero but very seldom does. These errors are due to the initial position error, various gyroscope and accelerometer errors and changes in the gravity field over which the system travels.

Kalman Filtering may be explained as follows. It is a mathematical technique (using differential equations) that uses a priori knowledge of the statistical nature of the errors contained in the determinations of positions thereby giving the best estimate of the system states. Accuracy of the system is increased when the sensor information from the inertial platform is compared with the information from an *external source*. If systematic changes develop, the Kalman Filter updates the a priori information and develops a new budget for the various error sources of the total navigation error. At the zero velocity update, the Kalman Filter looks at any residual output as a bias and from these resultant velocity errors it estimates how this bias developed with time. More detailed explanations of Kalman Filtering will be found in the references listed in this report.

When the vehicle arrives at a survey point at which geodetic parameters are required, the index mark of the system is placed over the point. The system, on command of the operator, does a ZUPT and stores the positional and other data as required by the program in the Data Storage Unit. This process is repeated at each survey point where positional data is required.

3c. **SMOOTHING MODE.** After data has been gathered at each of the required points, the mission must be terminated over a known control point (a different point than the one from which the system started). When the terminal station of the traverse is reached and the update performed (position and elevation entered into the CDU) there is a difference between the computed values and the real values despite the use of the Kalman Filter mechanization at each zero velocity update and at the various stations for which coordinates are being determined. These residual errors increase as a function of time, distance traveled, the route and type of terrain over which the traverse is being run and the interval between the ZUPTS. The principal error sources causing the residual errors are accelerometer scale factor, bias and misalignment, gyro bias and changes in gyro drift rate, and changes in the gravity field over which the system travels. Post mission smoothing is a mathematical mechanization used in an attempt to correct the effects of these residual errors on the computed positions at each of the stations at which the coordinates were established by the inertial system. Some organizations have developed their own post mission smoothing. Some of these are discussed in the references that are listed in this report.

4. **SYSTEM ACCURACIES.** The accuracy of inertial systems is dependent on many factors. Among these factors are system component errors, system mechanization errors, operator induced errors, environmental induced errors and basic horizontal and vertical control station errors.

There are many system component error sources. The effects of most of these error sources can be overcome by proper mathematical modeling. Some of these error sources are predictable gyro drift rate, scale factor, misalignment and g-sensitivity, as well as accelerometer drift rate, scale factor, misalignment and null uncertainty. System component error sources that cannot be cancelled by mathematical modeling can be grouped into what is generally termed as component sensitivity errors (an example is the smallest acceleration that an accelerometer is consistently capable of measuring accurately).

System mechanization errors are present only because the companies making inertial survey systems have not optimized the navigation equations in the original aircraft inertial navigation systems to a precise inertial survey system.

Like any other survey system, the results obtained with an inertial survey system can be effected by the person operating the system. However, the chances of errors, caused by the operator of an inertial survey system, are reduced to his action at the starting and ending stations of a traverse, and his care of operating the vehicle. Gross errors are only possible at the starting and ending stations. Operator errors are easily traced in an inertial system and can usually be eliminated when doing a post-mission adjustment.

The two largest sources of environmental induced errors are temperature changes, and the earth's changing gravity field. Gyroscopes and accelerometers are extremely sensitive to temperature changes. Very small changes in temperature cause a change in gyro drift rate and the rate of acceleration being measured by the accelerometers. The effects of internal temperature gradients (caused by heaters and heat generated by electronic components), as well as changes in electromagnetic fields generated by various electrical components are the probable main causes for changes in gyro and accelerometer output. These changes are difficult to eliminate using mathematical models, but can be partially compensated with proper modeling and further controlled by careful operation of the survey system.

The errors caused by the various system components (primarily the accelerometers) that sense the earth's changing gravity field as changes in acceleration of the system can be partially overcome by proper mechanization within the operational software. Also, further improvement can be made by utilizing information obtained from the inertial survey system during the mission in a post-mission adjustment.

All basic horizontal vertical control stations, regardless of how they were established, are not error free in reference to their absolute position to the starting or closing stations or any other control point. This positional uncertainty can be from 1 or 2 centimeters to as much as 1 meter depending on how the control points were established. Since inertial systems must start and end each mission on different control stations, consideration must be given to the accuracy of these stations to each other. That is why it is recommended that only first order control points be used to initiate or terminate inertial survey missions.

A considerable amount of horizontal and control data obtained with various inertial survey systems has been analyzed. This data was obtained during testing of the inertial systems over courses containing high order control stations. Comparisons of the values obtained with the inertial systems against the published values for the control stations gave the following; for closely controlled single run traverses, a difference for horizontal values of 20-25 centimeters was seen and a difference for vertical values of 8-12 centimeters was seen; for multi-run traverses (3-5 forward and reverse runs), a difference for horizontal values of 10-15 centimeters was seen and a difference for vertical values of 3-6 centimeters was seen. A few special tests were run using 1 to 1 1/2 minutes between zero velocity updates. These tests showed no improvement in horizontal positioning, but vertical positioning was greatly improved showing a difference of only 2 centimeters for single run traverses and a 1 centimeter difference for multi-run traverses between the inertial and the conventionally established stations.

At the present time, USAETL is working to improve the inertial survey systems accuracy by having accelerometers with greater sensitivity installed in their inertial survey system. Preliminary analysis indicates that horizontal accuracies of between 5-10 centimeters will be obtainable with these more sensitive accelerometers.

5. LITTON AUTO-SURVEYOR (LASS). The Auto-Surveyor is officially known as the Litton Auto Surveyor System (LASS). It was designed and built by the Litton Guidance and Control Systems primarily for the commercial market. It is a modification of the original advanced development prototype PADS built under contract for USAETL. LASS requires a 24-volt power system with an initial power requirement of 2200 watts for about 4 minutes followed by a steady-state power requirement of approximately 600 watts. Figures 12 (a), 12 (b), and 12 (c) illustrate the LASS.

A total of 12 systems have been built to date. SPAN, Inc., of Scottsdale, Arizona, has 5 systems. The United States Bureau of Land Management (BLM) has 3 systems. The Canadian Department of Energy, Mines and Resources (EMR) has 1 system. The Defense Mapping Agency (DMA) has 1 system. USAETL has 1 system and 1 system has been kept by Litton. All of the above systems have the same basic units listed in figure 12 (a). Some organizations have made some modifications to their systems, such as integrating distance measuring devices to the IMU, adding hover sights for helicopter operations and modifying the software for specific uses. With these modifications came name changes.

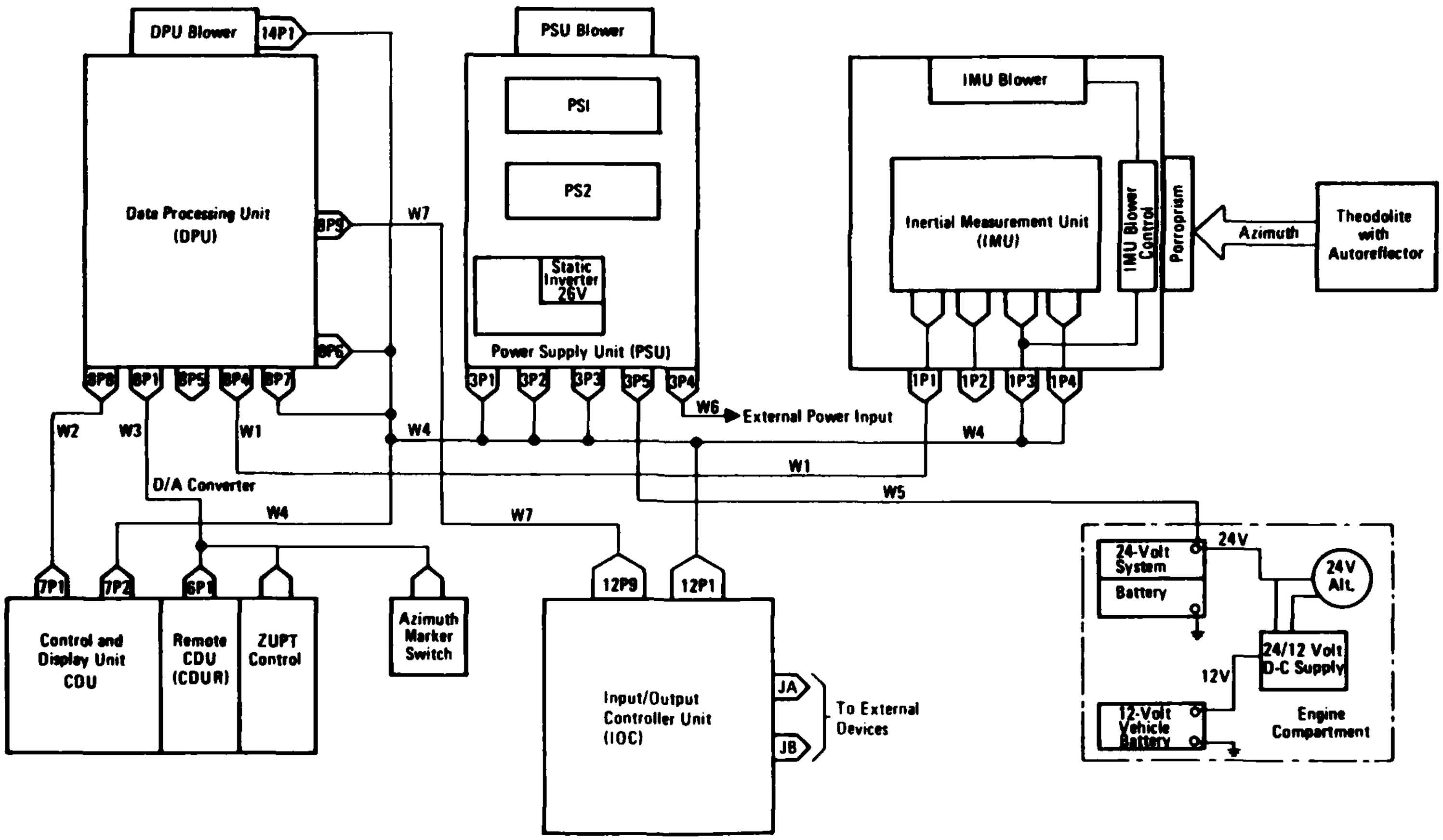


Figure 12 a. Litton Auto-Surveyor System (LASS)

Figure 12 b. LASS Mounted in Ground Vehicle

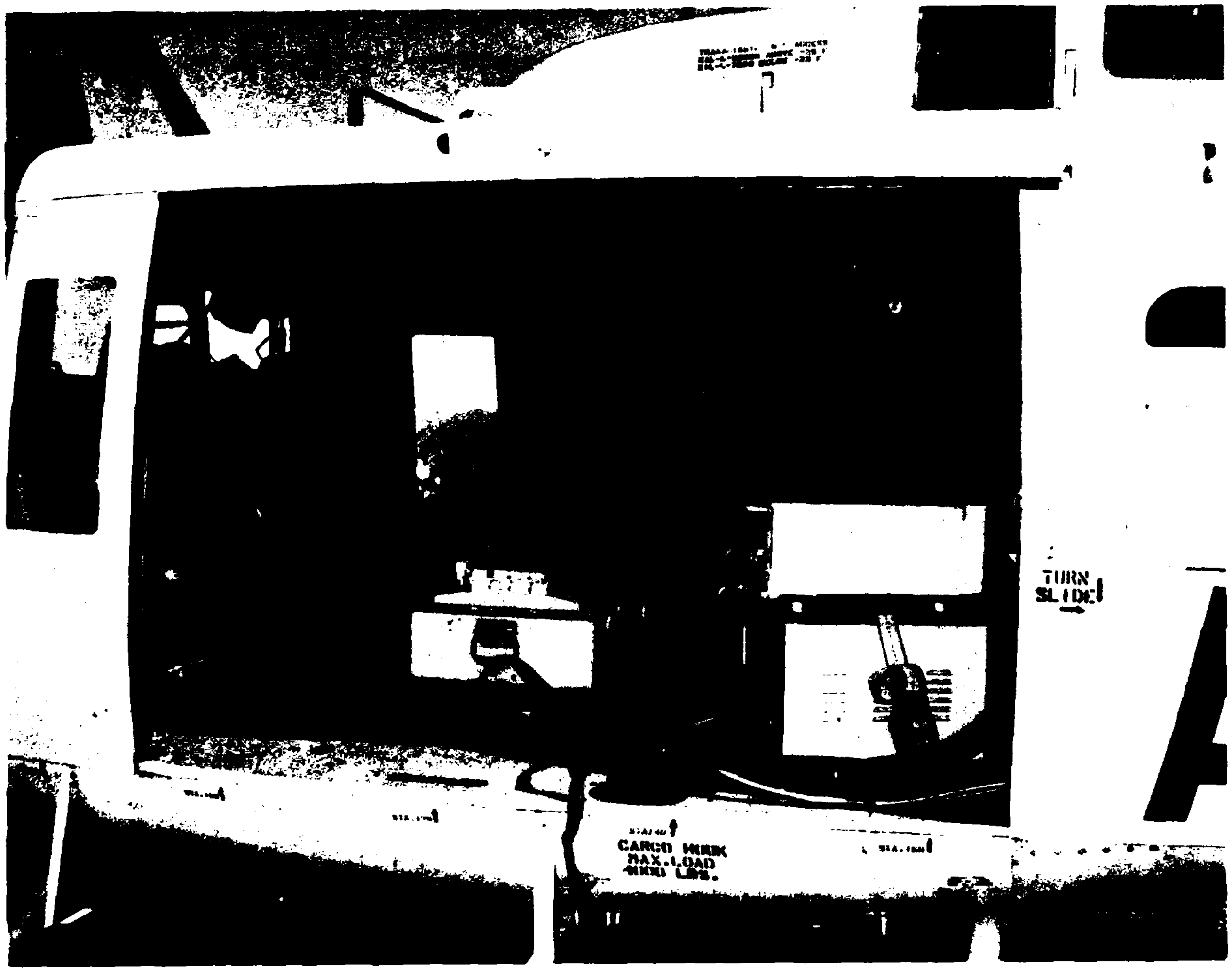


Figure 12c. LASS Mounted in Helicopter

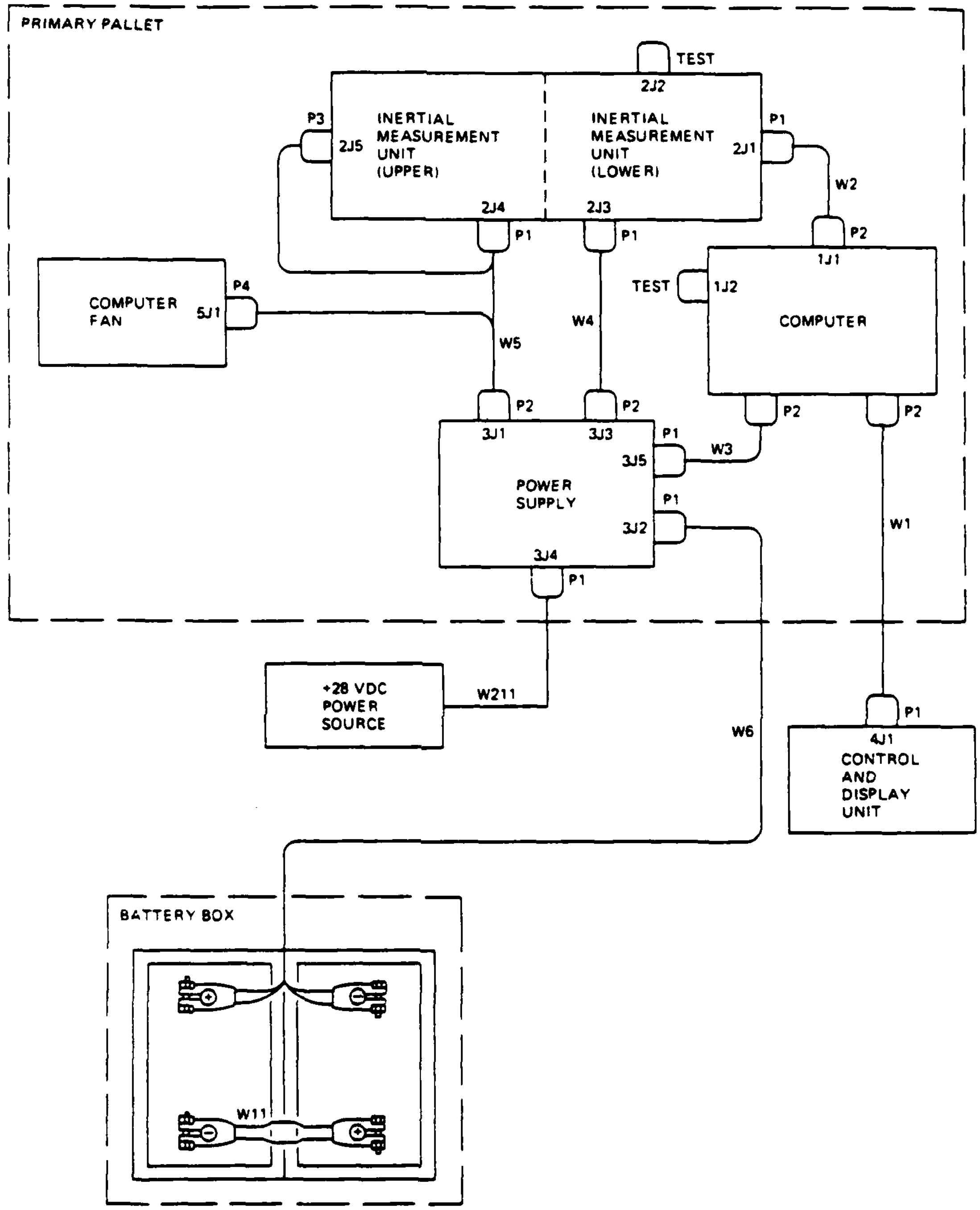


Figure 13a. PADS System Diagram

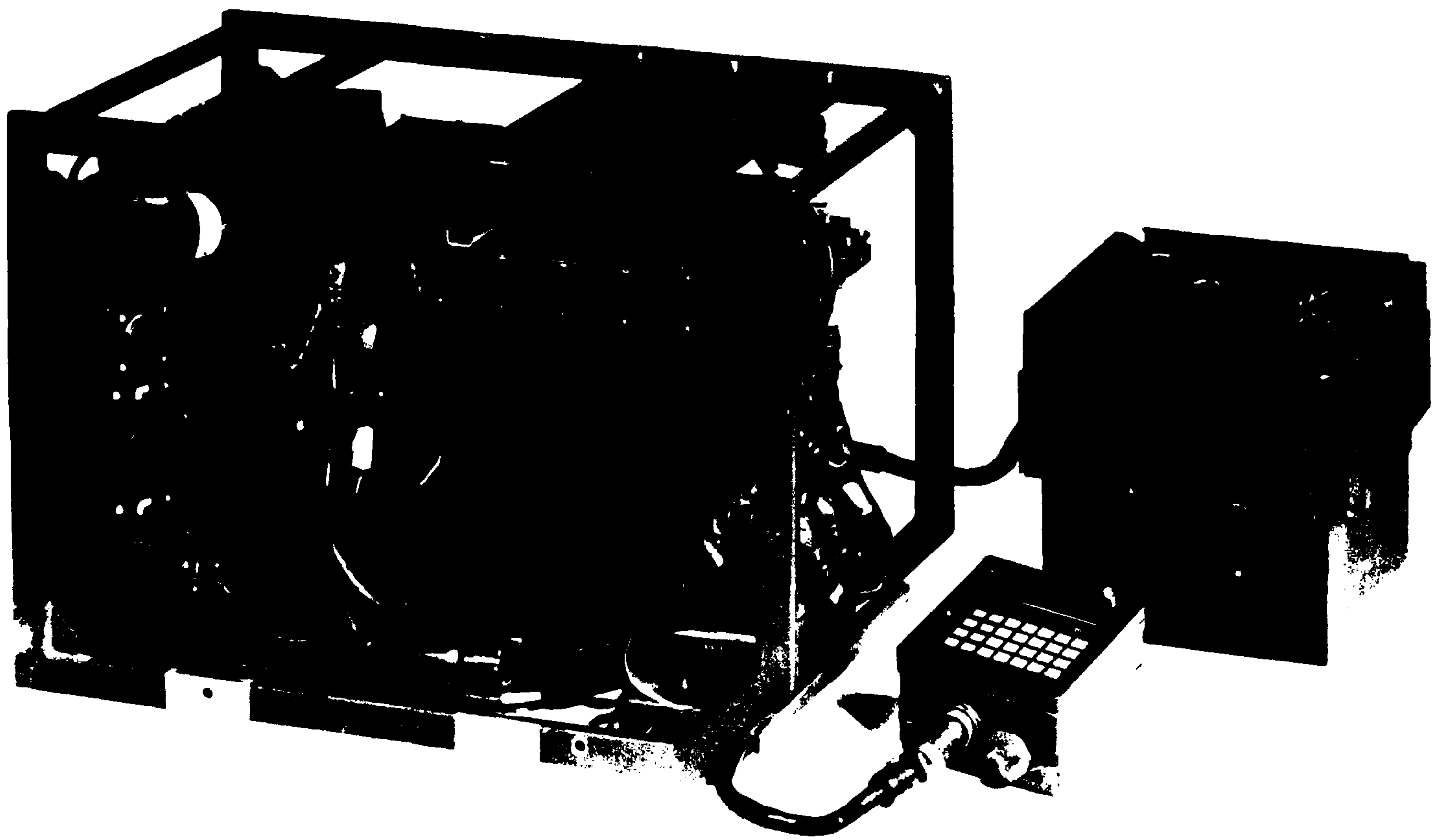


Figure 13b. PADS System

SPAN, Inc. calls its system SPANMARK. EMR of Canada calls its system the Inertial Survey System (ISS). DMA calls its system the Inertial Positioning System (IPS), and USAETL calls its system the Rapid Geodetic Survey System (RGSS). The LASS installed in a ground vehicle and helicopter is shown in Figures 12 (b) and 12 (c).

Litton is now building a new version of its Auto-Surveyor System to be known as LASS II. This version will be based on the production model of the PADS presently being built for the United States Army, for use by survey personnel who are responsible for positioning requirements with the Field Artillery. A total of 102 PADS are being built under the initial production contract. The LASS II is being built to the following specifications: (1) horizontal accuracy of ± (15 cm + 1/10,000 of the distance to the nearest known control station), and (2) vertical accuracy of ± (12 cm + 1/12,000 of the distance to the nearest known control station).

The cost of the LASS II in 1981 dollars is 1.2 million dollars for the first system with each system thereafter costing 0.5 million dollars. The 1.2 million for the first system will include spare parts, operator and maintenance manuals, training in the operation and maintenance of the system, and a warranty period. The production PADS that LASS II will resemble is shown in Figures 13 (a) and 13 (b). The power requirements for LASS II will be approximately the same as those required for LASS.

6. **HONEYWELL GEO-SPIN.** The GEO-SPIN Inertial Survey System is manufactured by the Avionics Division of Honeywell Inc., and is a modification of the SPN/GEANS, a high precision inertial navigation system presently being built for the United States Air Force. Honeywell is under contract to build a total of 900 SPN/GEANS for the United States Air Force for use in various multi-engine aircraft.

One GEO-SPIN inertial system has been built and delivered to the Defense Mapping Agency. Honeywell Avionics is presently under contract to build two GEO-SPIN systems for World Surveys Inc. The basic units of the GEO-SPIN are shown in Figure 14 (a). The GEO-SPIN requires a 24-volt power system with an initial power requirement of 3600 watts for a few minutes followed by a steady-state power requirement of approximately 1200 watts. The GEO-SPIN installed in a ground vehicle and helicopter is shown in Figures 14 (b) and 14 (c). The accuracy specifications to which the GEO-SPIN is being built are: (1) a low-density survey with a maximum of 50 points for a 40-mile traverse with a maximum error of 90 centimeters in both horizontal and vertical (design goal accuracy will be 45 centimeters). These specifications are for using a ZUPT interval of 4 minutes. If a ZUPT interval of 2 minutes is used, an improvement of 30 percent should be realized, (2) a high-density survey using a traverse length of 6 miles will show a maximum error of 25 centimeters in horizontal and vertical (design goal accuracy will be 15 centimeters). These specifications are for a maximum of 25 points.

The cost of the GEO-SPIN in 1981 dollars is $625,000 for the system, with an additional $25,000 for operator training and manuals. Two maintenance options are available and are shown in Figure 15. Option I is maintenance on-call by Honeywell and Option II is maintenance to be performed by the customer.

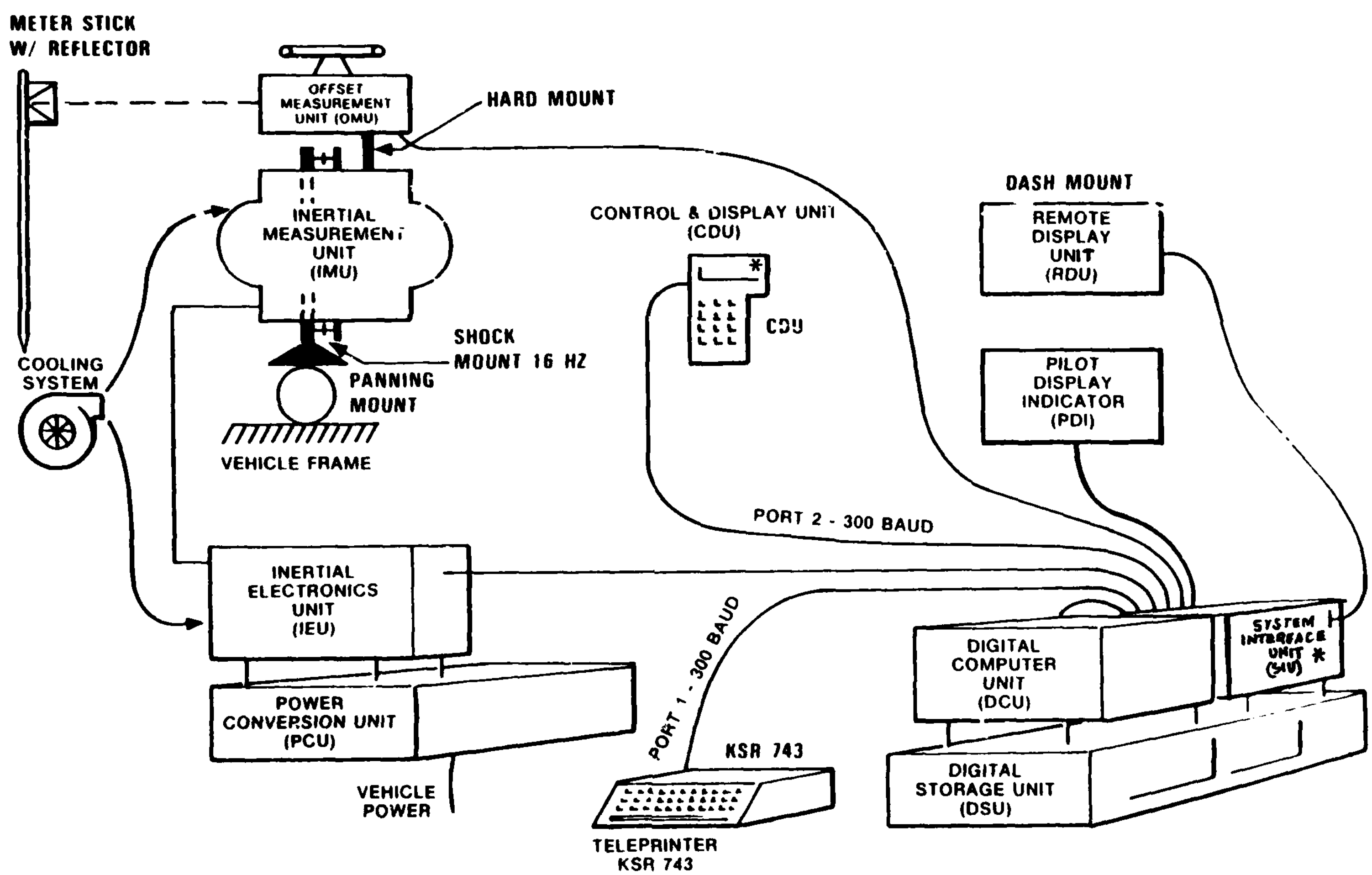


Figure 14a. GEO-SPIN Inertial Survey System Diagram

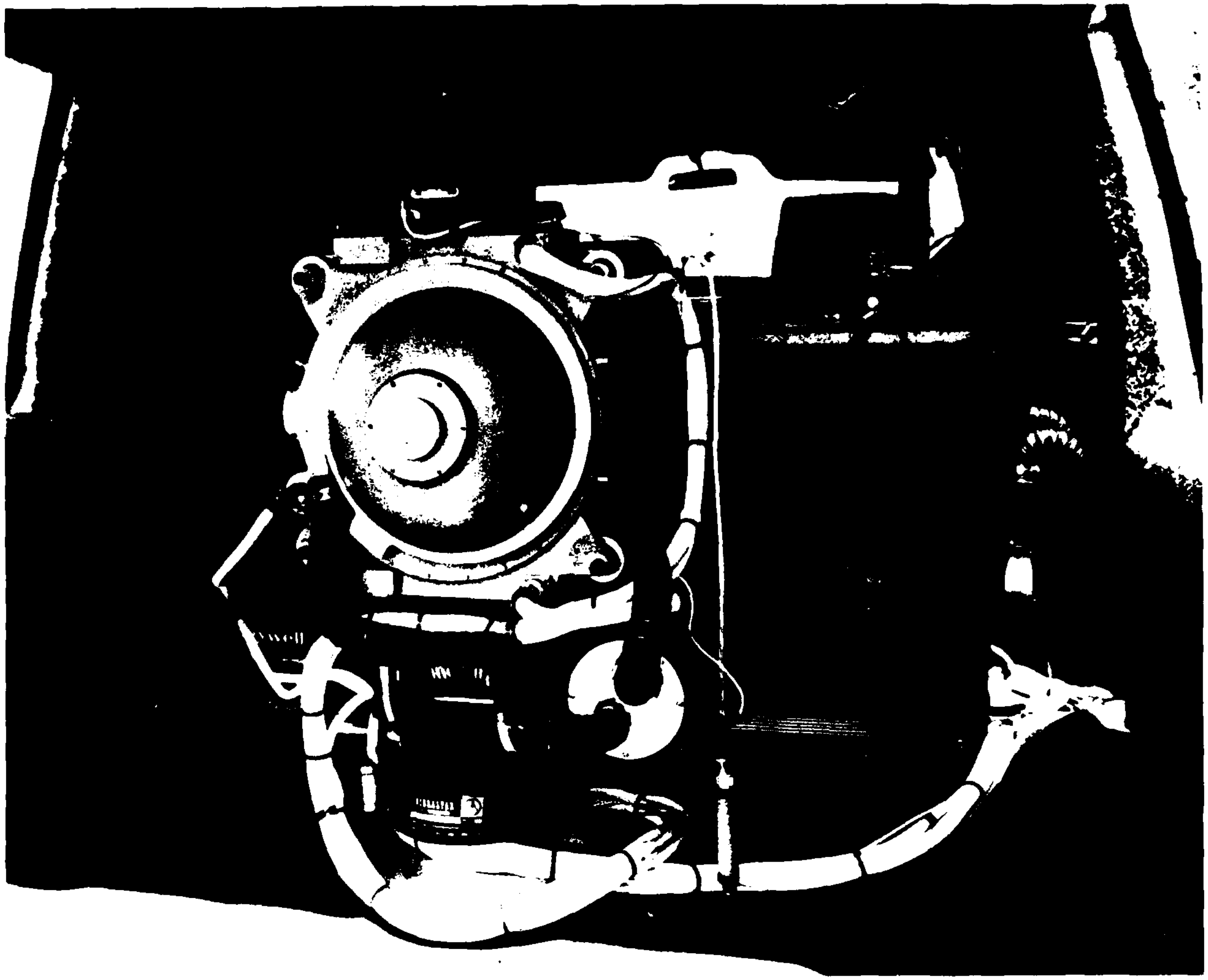


Figure 14b. GEO-PIN Mounted In Vehicle

Figure 14c. GEO-SPIN Mounted In Helicopter

MAINTENANCE OPTION I (FULL WARRANTY)

ROTATABLE SPARES	$ 260 K
YEARLY COST (INCLUDING SPARES STORAGE AND REPLACEMENT)	$ 250 K

MAINTENANCE OPTION II (CUSTOMER-SUPPORTED REPAIRS)

SPARE STOCK	$ 550 K
MANUALS	$ 22 K
O&M TRAINING COURSE	$ 33 K
SUITCASE TESTER	$ 25 K
YEARLY COST	
LIGHT USE (50-100 HRS/MO)	$50-75K
HEAVY USE (100-200 HRS/MO)	$75-100K

Figure 15. Honeywell Maintenance Options

7. **FERRANTI INERTIAL LAND SURVEYOR (FILS).** The Ferranti Inertial Land Surveyor evolved from the British Military PADS, which in turn evolved from military aircraft systems designed for the British Armed Forces by Ferranti Limited of Great Britain. At present, three FILS-2 and two FILS systems are in operation with Shell Canada Resources, Limited. The system is shown in Figure 16. Smoothing cannot be accomplished immediately after completion of the traverse. During the traverse, all the data is transferred to a digital cartridge recorder for post-mission smoothing at a central processing point. Since FILS-2 is not made in the United States it is not being considered for purchase by the Corps at this time.

8. **USGS AERIAL PROFILING OF TERRAIN SYSTEM (APTS).** The Aerial Profiling of Terrain System is being developed by the Charles Stark Draper Laboratory, Inc., for the United States Geological Survey to provide a precise airborne survey system capable of measuring elevation profiles across various types of terrain from a medium to light aircraft at flight heights up to 1000 meters above the terrain. The systems design accuracy goals are a horizontal position accuracy of 60 centimeters and a vertical position accuracy of 15 centimeters with 90 percent reliability level.

The airborne instrument package, shown in Figures 17 (a), 17 (b), and 17 (c) contains a three-gimbal inertial platform to define the position of the aircraft in three coordinates. A two-axis laser tracker is used to determine long-term drift errors of the inertial platform (the laser tracker will provide the external-aided information similar to the ZUPT data described previously). Three or more positioned retroreflectors over known stations interspersed with several other reflectors (positioned by the laser tracker) will provide ground truth. The inertial platform and laser tracker will provide the position datum and a laser profiler will perform distance measurement from the aircraft to the terrain.

The APTS is one of a kind system and at the present time cannot be considered for use as an inertial survey system for the Corps due to the high cost of purchase and maintenance.

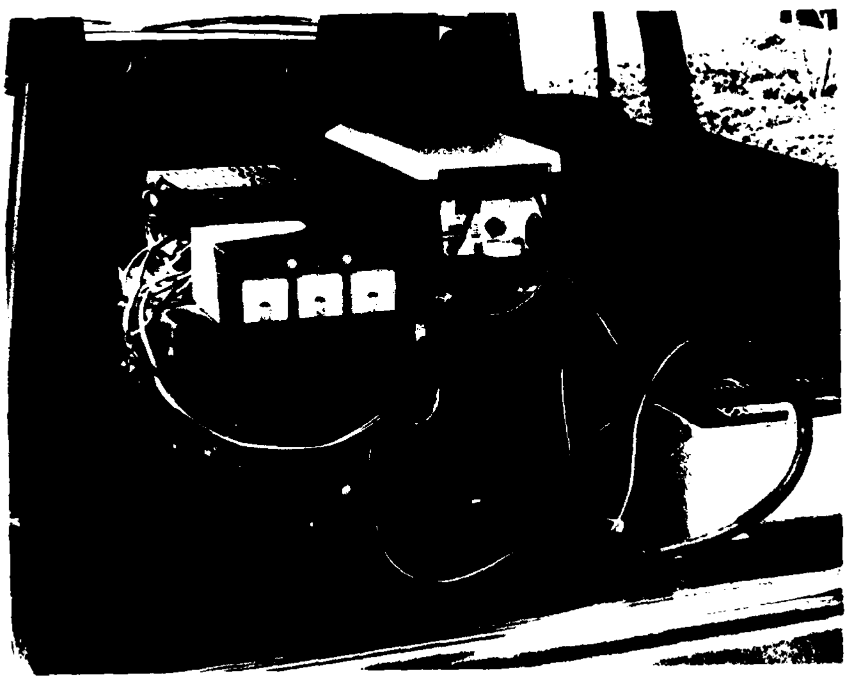


Figure 16. Ferranti Inertial Land Surveyor (FILS)

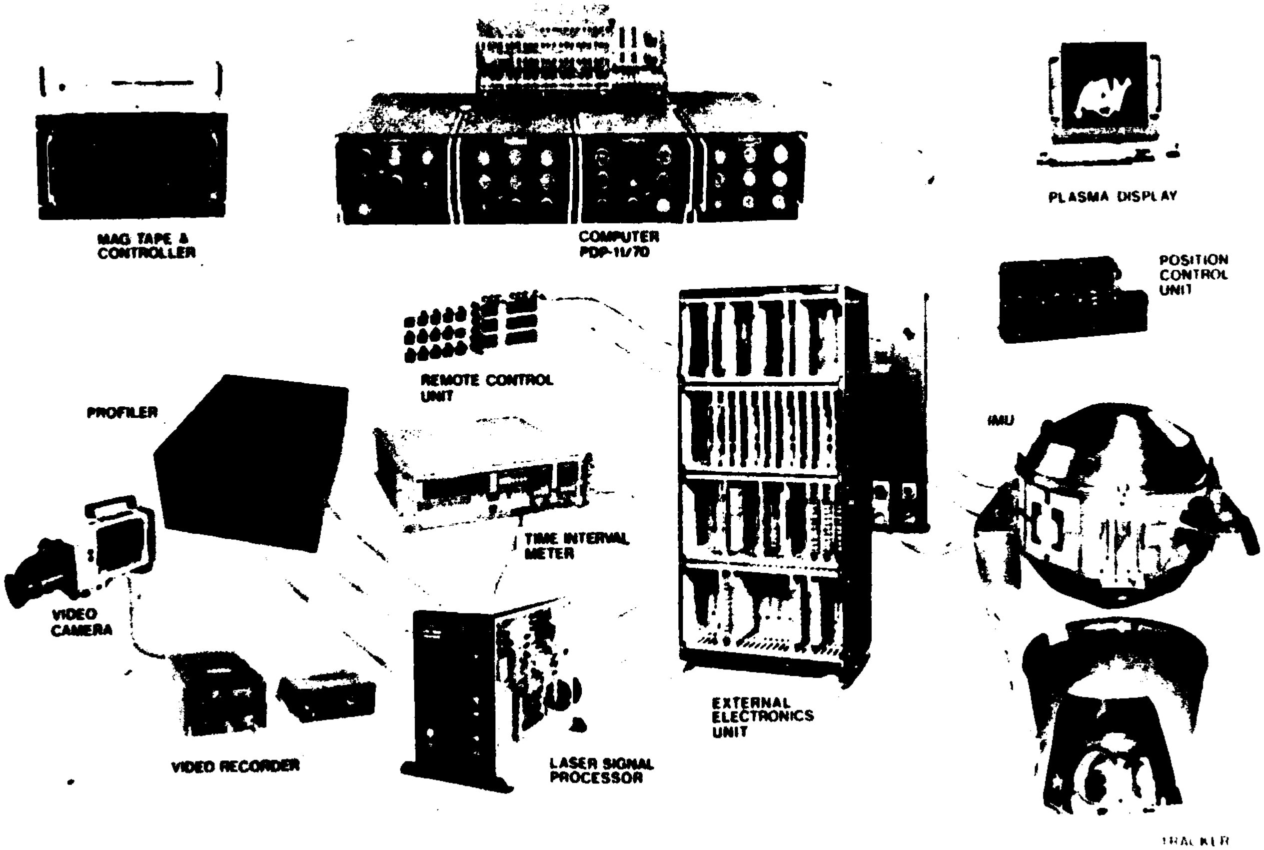


Figure 17a. Aerial Profiling of Terrain System (APTS) Major Assemblies

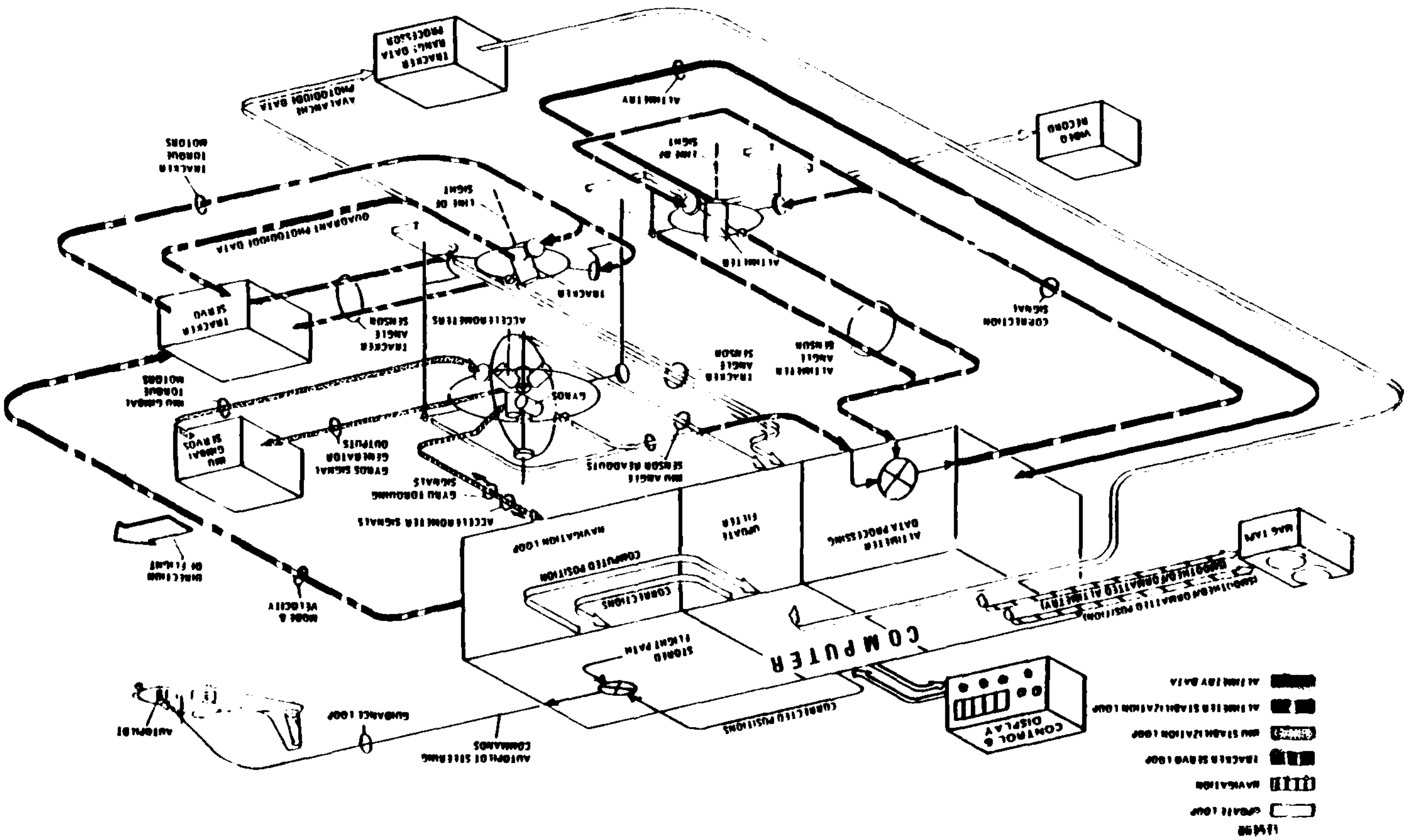


Figure 17b. APTS Functional Diagram

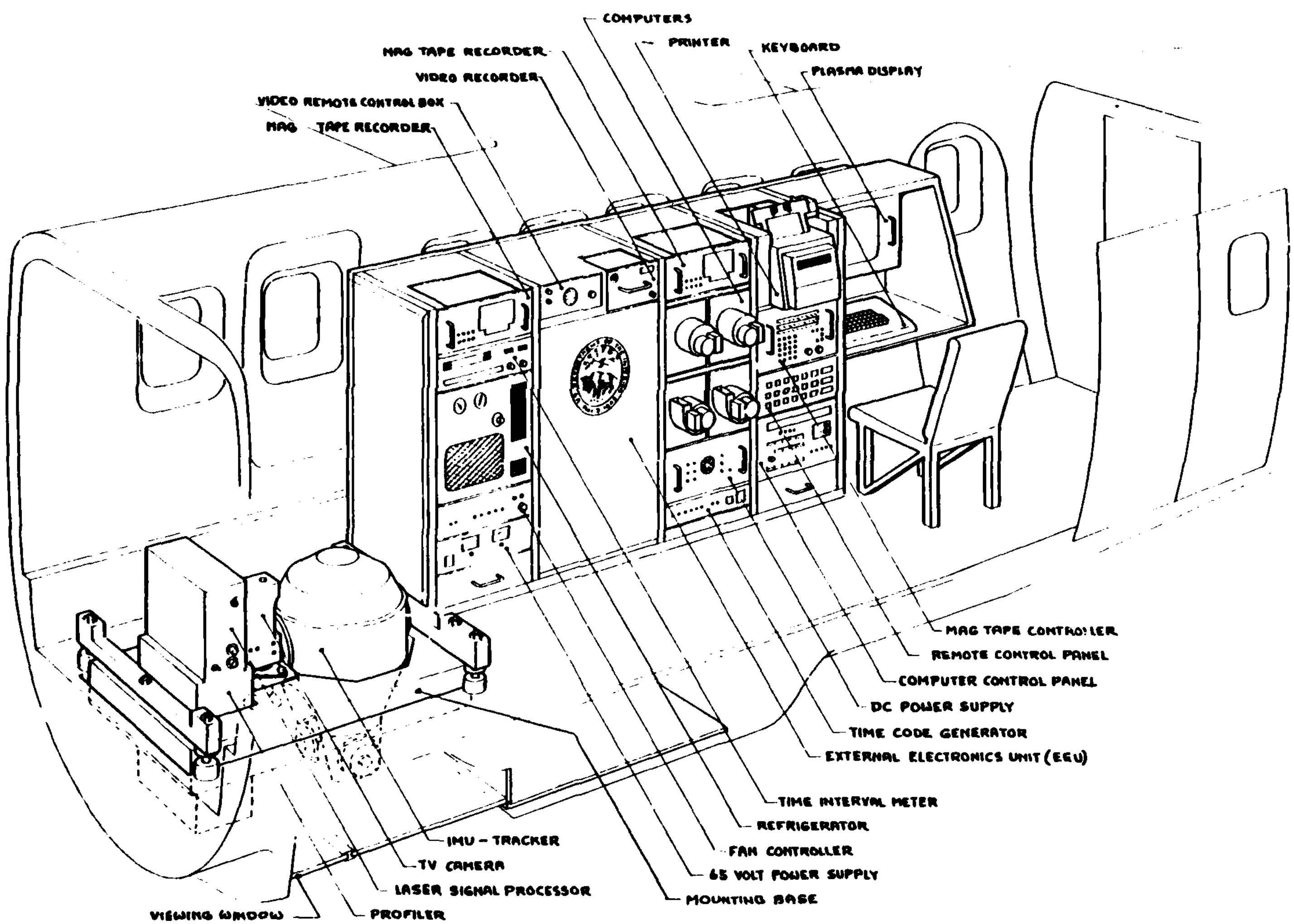


Figure 17c. APTS Installation In Aircraft

IV. OPERATIONAL RESULTS IN THE USE OF INERTIAL SURVEY SYSTEMS

1. **GENERAL.** The extensive use of inertial navigation systems for surveying purposes started in 1975. Since that time, they have been mounted in trucks, tracked vehicles and helicopters and have operated from the northern slopes of Alaska and Canada, in extreme cold weather, to the hot deserts of Saudi Arabia. The systems have been used to determine land boundaries in the wilderness of Alaska; to position survey markers in cities; to establish basic geodetic control; to provide control for various types of mapping; to assist in route selection of roads, railroads, pipelines and electrical transmission lines; and to obtain positions in geophysical work for gravity and seismic surveys. The following portions of this chapter will deal with the operational results of inertial survey systems by various United States and Canadian Government agencies as well as private companies engaged in inertial survey work.

2. **UNITED STATES ARMY.** The United States Army has awarded a contract to Litton Systems, Inc. for delivery of approximately 102 PADS for use by the Field Artillery. The PADS will greatly enhance the capability for the Artillery to survey positions for various weapons systems. The Field Artillery School used one of the developmental PADS for training purposes for a year. During this period they were requested to do two survey projects. One survey project was at the National Training Center, Fort Irwin, California, and the other project was at Fort Chaffee, Arkansas.

A team of two soldiers, using a 1/4-ton truck-mounted PADS, began the survey at the National Training Center on 15 October 1980, and finished the job on 5 November 1980. During this period, they surveyed 450 miles and established a total of 1250 control points in an actual work time of 17 days. In comparison, a conventional survey party of 7 people would require 100 days to accomplish the same task.

The second survey task was to locate 34 survey control points at Fort Chaffee, Arkansas. A reconnaissance of the area (extensively wooded), indicated that a conventional survey party (7 people) would require about 3 weeks to complete the survey. The PADS was airlifted from Ft. Sill, Oklahoma to Fort Chaffee where it completed the survey mission in less than 6 hours.

3. **DEFENSE MAPPING AGENCY.** Operational testing of the Litton inertial survey system known as the Inertial Positioning System (IPS I) was completed in early 1976, when the system became operational for production purposes. Since that time, the system has accomplished various types of projects, which are listed in Table 1.

The system was used in various carriers from 4-wheel-drive vehicles to helicopters over all types of terrain. An analysis of an MX support survey accomplished in the August-November 1978 time frame, with the system mounted in a helicopter, shows an average daily production rate of 20 stations per day with a high production of 60 stations for one day. The data collected during this period shows horizontal positions accurate to 0.5 meters and elevations accurate to 0.3, meters which satisfied the project requirements. To obtain these accuracies, the helicopter was flown in fairly straight lines between the initial and terminal update points. ZUPTS were done every 3 minutes and traverse lengths were held to distances under 45 kilometers. Each traverse was double run. Greater accuracy could have been obtained by using a shorter time interval between ZUPTS and placing the IMU on the ground when performing ZUPTS and updates.

Table 1. DMA Projects Completed With IPS I - March 1976 - April 1981

PROJECT	LOCATION	POINTS	KILOMETERS	MAN-YEARS SAVINGS
Aircraft Navigation	Southeast U.S.	5	480	0.5
Test Range	California	43	970	1.0
Aircraft Navigation	Wyoming	5	1,210	0.5
Aircraft Points	Michigan	28	80	0.3
Mapping Surveys	Maine	329	2,900	4.0
Aircraft Points	N. Central U.S.	264	645	1.5
Mapping	Yucatan, Mexico	371	4,345	5.0
Test Range	Louisiana	100	300	0.6
Aircraft Navigation	North Dakota	1	80	0.2
Radar Site Survey	Korea	507	1,860	5.0
MX Support	Western U.S.	1,035	6,200	5.0
Weapons Range	Oklahoma	465	400	2.0
Gravity Surveys	California	700	1,010	4.0
Cruise Missile Survey	Missouri	9	350	2.0
MX Support	Western U.S.	1,320	3,000	1.5
TASVAL	California	13	635	1.0
MX Validation	Nevada/Utah	3,200	22,400	24.0
TOTALS		8,395	46,865	58.1

To-date, an estimated total of 58.1 man-years have been saved by DMA with the use of IPS I. The original cost of IPS-I was $605,000 with an additional $400,000 being spent for spare parts and maintenance. An additional $100,000 must be charged to transportation other than the basic vehicle (primarily helicopter time). This brings the cost of the inertial system use to $1,105,000 since 1976. The average total cost (salary, overhead and benefits) of a surveyor for 1 year will conservatively be figured at $35,000. A savings of 58.1 man-years by using the IPS translates to a dollar savings of $2,033,500.

In September 1979, Honeywell delivered their GEO-SPIN system to DMA. Since that time the system has been undergoing extensive test and evaluation. Excellent positional accuracies have been obtained with the system. On courses with a length of 32 kilometers, the system shows an accuracy of 0.5 meters in horizontal positions and 0.3 meters in elevations. The system is undergoing some modifications and further testing.

4. **BUREAU OF LAND MANAGEMENT.** The U.S. Department of the Interior, Bureau of Land Management (BLM) completed testing the Litton Auto-Surveyor in 1975. These tests were conducted to determine if the inertial system could be used to perform cadastral surveys for the United States Government, as well as, being used to monitor contractors doing cadastral surveys. The Litton Auto-Surveyor was sent to Alaska. Since most of the cadastral work to be done in Alaska was in remote areas, the system was mounted in a helicopter.

The primary task to be accomplished was the establishment of section corners every 2 miles on the exterior lines of townships. Normal production for the inertial survey system in Alaska is about 36 section corners over traverse lengths of 70-80 miles. On exceptionally good days, a total of 100 corners over traverse lengths of 200 miles have been obtained. A conventional survey crew would average 4 to 6 points over traverse lengths between 6 to 10 miles.

BLM has been so impressed with the operation of the Auto Surveyor that additional units have been purchased. A total of three sytems are now being operated by BLM. The systems are used in Alaska during late spring, summer, and early autumn. The rest of the year, the units are refurbished and used on projects in the western United States. BLM officials of the Anchorage Office feel that Inertial Survey Systems will decrease the time needed to finish the basic work in Alaska by 50 percent.

5. **CANADIAN DEPARTMENT OF ENERGY, MINES AND RESOURCES.** The Geodetic Survey Division of the Canadian Department of Energy, Mines and Resources (EMR) purchased an inertial survey system from Litton in 1975 for the purpose of producing mapping control faster and more economically. The year 1975 was spent conducting a series of tests to define operational procedures and to train the required personnel. Tests were performed using both vehicle and helicopter mode. The helicopter mode of operation was used for almost all major projects which included establishing basic control as well as mapping control.

The inertial system was operated under the following guidelines: (1) intervals between ZUPTS of 3 to 4 minutes allowing a station spacing of 6 to 11 kilometers. (2) Traverse lengths between control updates of 80 to 100 kilometers. (3) A limit of 4 to 5 hours between premission updates.

The first group of projects (1976-1977) are listed in Table 2. The Vancouver Island project was performed in the vehicular mode and was for vertical control only. The elevations of the stations ranged from 10 meters to 313 meters. A total of 16 existing first-order level stations were included in the various lines. The comparison between inertial determined elevations and differential leveling was excellent, with the largest difference being 35 centimeters. The RMS error for the comparison is 10 centimeters.

Table 3 shows a Project Cost Analysis (cost includes planning, depreciation of equipment, transportation, etc.). Some of the costs seem high, but it must be remembered that many of these projects were in remote areas. In the 1979 Manitoba project, extreme weather conditions and a helicopter crash are the primary reasons for the high cost.

Canadian officials state that in the most favorable circumstances, (grid-type control surveys covering large areas of prairie) savings of 50-65 percent were realized in comparison with the cost of the best alternative conventional surveying methods. The inertial survey system, with spare parts, paid for itself during the first two field seasons.

Table 2. Analysis for 1976 and 1977 Canadian EMR Projects

PROJECT	TURNER LAKE TRAVERSE	VANCOUVER ISLAND VERTICAL	SADDLE LAKE	PRAIRIE MAPPING
Number of Points	25	430	80	445
Traverse Length Km)	473	1,750	560	5,600
Time (Weeks)	5	6	1.5	7
Cost/Station (Inertial)	$ 1,140	$ 297	$ 670	$ 877
Cost/Station If established conventionally (Estimated)	$ 2,400	$ 400	$ 1,000	$ 1,500

Table 3. Canadian EMR Project Cost Analysis

	AREA	STATIONS	COST STATION
1977	Artic NWT	116	$2,482
	Central Manitoba	60	$3,037
	Alberta & Saskatchewan	199	$1,741
1978	Quebec	171	$857
	Ontario/Manitoba	218	$3,112
	Alberta	262	$1,545
	Saskatchewan	590	$1,261
	Alberta (Ice Cap) (Vertical Only)	68	$859
1979	Alberta	793	$1,315
	Saskatchewan/Alberta	590	$1,792
	Manitoba	22	$6,672
1980	Maritimo	160	$1,556
	Manitoba/Saskatchewan	364	$1,232
	Alberta	449	$2,036
	Victoria Island (Artic Mapping)	62	$4,822

6. **SPAN INTERNATIONAL, INC.** SPAN has been in the business of inertial surveying since 1975. Since that time, they have grown from a company with one inertial system to a company with five inertial survey systems. The company has provided SPANMARK (their modification of the Litton Auto-Surveyor) service worldwide. Their systems have worked on the north slopes of Alaska, Canada, Central America, Middle East, and the United States. A summary of the type and amount of work accomplished by SPAN using inertial survey systems is shown in Table 4. A partial list of projects on which SPANMARK was used is shown in Table 5. Three projects that the SPANMARK System was used on will be discussed in more detail. One project was control on a 30-mile section of the high speed mainline track between Washington, D.C. and Baltimore, Maryland. The other two projects were geodetic control surveys for the National Geodetic Survey in Louisiana and Arizona.

Maddox, Inc., working as a subcontractor to DeLenaw Cother/Parson, a general engineering consultant to the Federal Railroad Administration, leased the SPANMARK System for a project of track rehabilitation design along a 30-mile section of the Northeast Railroad Corridor between Washington, D.C. and Baltimore, Maryland. The work had to be completed in 6 weeks in which all the field data had to be accumulated and turned over to the prime contractor. Included in the 30-mile project were 87 miles of mainline track having 14 curve sections totaling 29 miles. The distance between data points on the straight sections was 275 feet and the distance between data points on curves was 50 feet. In addition, all frogs, switches, cross-overs, and sidings were positioned. The survey also included the location of approximately 1100 catenary towers, culverts, manholes, bridge abutments and other obstructions. The work had to be accomplished without interrupting traffic on the main lines, which meant that most of the work was accomplished at night totalling 3 1/2 to 4 hours a night. In spite of the difficulties, the work was accomplished within the alloted time frame. The inertial determined positions checked very closely with the survey data determined conventionally in the overlapping sections of the project.

Table 4. SPAN Project Experience

TYPE	POINTS	TRAVERSE LENGTH (kilometers)
1. Control Surveys	5,540	29,983
2. Mapping (Aerial Photo Control)	14,665	35,508
3. Legal Surveys	5,730	47,657
4. Construction Surveys	10,174	28,380
5. Geophysical	63,183	101,093
6. Profile Surveys	161,287	4,811
7. Land Data Systems	1,034	8,274

Table 5. Sample Listing of SPAN Projects

USER	APPLICATION	REMARKS
Mexico City, Mexico	Control Extension, Densification and Engineering Terrain Data	98,000 XYZ terrain data points of profiles. Data supplied on computer compatible mag tape for automatic plot of plans and profiles.
Tegucigalpa, Honduras	Cadastral Mapping Control Base	Control was densification of existing control nets and formed geodetic base for land ownership mapping.
Geophysical Services, Inc.	Position and Elevation Data for Seismic Surveys Surveying done at time in -60 degree F weather.	14,484 kilometers of traverse on North slope, Alaska.
Exploration Data Consultants	Position and Elevation Data for Gravity Meter Readings	Some 12,000 locations were determined.
GENGE Aerial Survey	Establish basic control for a strip 730 miles long by 4 miles wide in Saudi Arabia alignment and construction purposes. The control extended from the Persian Gulf to the Red Sea.	The unified net of control later used for photomapping
TENNECO	Horizontal and Vertical Control Extension and Densification	A total of 2,200 points in a 500-mile corridor from Pennsylvania to the Canadian border were established.
TENNECO	Horizontal and Vertical Control	1,200 kilometer route for a natural gas pipeline was run with a total of 1,288 points established.

Table 5. Continued

TELEDYNE U.S. Bureau of Reclamation	Geotronics for Extension of Horizontal and Vertical Control	400 points were established for controlling photogrammetrically compiled topographic maps at a scale of 1:1,000 and 0.5 meter contour interval along a series of existing and to be built canals in Utah.
Northwest Survey for Alberta Department of Lands and Forests	Horizontal and Vertical Control	40 points established in a 2,500-square mile area for analytical aerial triangulation and land ownership monumentation.
Beliveau - Couture & Samson - Monaghan	Geodetic Control Densification	250 monumented and targeted points were controlled by 2,500 kilometers traversing for a 1:20,000 scale mapping project.
Beliveau - Couture	Horizontal and Vertical Control	335 targeted points were positioned for 1:5,000 mapping at selected site in a 400 km by 500 km area.

The two projects accomplished for the National Geodetic Survey were basic horizontal control projects, one in south Louisiana and the other in southwest Arizona. The south Louisiana project was conducted along the Louisiana Gulf Coast. The traverse was 480 kilometers long and comprised 92 stations. The system was mounted in a helicopter and was used during periods of strong wind, near zero visibility caused by fog, moonless nights and during heavy rains. After the start of the project, no days were lost due to weather. The helicopter used flotation landing gear because of the type of terrain on which the survey was conducted. The work was accomplished in a 2-week period. During the project, 3 stations were recovered that had been assumed destroyed for the past 20 years. The rate of progress, related in terms of stations established per man-month using the inertial system, was valued at 12 compared to the average of 0.6 using conventional methods. The cost per station of this project is approximately $1,268 per station, or one-third the cost of conventional surveys. To evaluate the Inertial Survey System precision, 22 known stations (second order) were included in the coastal traverse. A comparison of the coordinates of these 22 points show 50 percent of the stations have relative accuracies of better than 1:50,000 with 60 percent better than 1:40,000. In all cases, the relative accuracies were better than 1:20,000 satisfying Second Order, Class II closure requirements with one half of the stations satisfying the 1:50,000, Second Order, Class I Standards.

The southwest Arizona project was a joint venture of NGS and SPAN. The project was undertaken to develop inertial survey specifications and to compare inertial survey results against the best available classical horizontal control (transcontinental traverse). One of the project's goals was to test the system over a distance of 80 kilometers, typical spacing between first-order control in the U.S. A section of the transcontinental traverse with a north-south leg and an east-west leg, each leg being approximately 80 kilometers long, was selected. Like the Louisiana project, all the work was accomplished in a helicopter. Analysis of the data has not been completed, but preliminary analysis once again shows Second Order, Class II for all stations with at least 50 percent meeting the accuracy requirements for Second Order, Class I surveys.

For leasing their SPANMARK system, SPAN is presently charging a $17,000 mobilization fee with a daily 7-hour actual use fee of $5,100. SPAN is changing company policy and in the future will bid on doing a total survey job rather than just leasing their systems.

7. **US ARMY CORPS OF ENGINEERS/CIVIL WORKS.** Inertial survey technology has been used by five of the Civil Works Districts. SPAN was involved in four projects, three projects were awarded to SPAN directly and in the fourth project SPAN was a subcontractor to Maddox, Inc. The fifth project was accomplished by the US Army Engineer Topographic Laboratories (USAETL) with their Rapid Geodetic Survey System (RGSS).

The first of the three projects accomplished directly by SPAN was for the Portland District. This project consisted of two parts. The first part was the establishment of horizontal coordinates for 160 monumented section corners falling on both sides of the Columbia River. The second part of the project was providing 400 horizontal and vertical control points for a flood plain mapping project in Washington County just south of Portland. This project cost $135,000 and was finished in less than 1 1/2 months. It was estimated that it would have cost $260,000 to do the same work using conventional surveying techniques.

The second project by SPAN was the extension of horizontal control for the Huntington District. This control consisted of 81 monumented stations along seven reservoirs and paralleling two rivers and required over 1,500 miles of traverse. This project was accomplished in 2 weeks.

The third project by SPAN was for the Louisville District and consisted of the establishment of horizontal and vertical coordinates for photogrammetric purposes in conjunction with a Federal Wild Rivers Mapping Project.

The fourth project which SPAN accomplished was as a subcontractor to Maddox, Inc. of Bethesda, Maryland who had been awarded a contract to obtain controlled profiles for approximately 240 miles of levee crowns along the Mississippi River within the New Orleans District. The accuracy required by the contract was that each profile point be established with a horizontal accuracy of $\pm$ 0.15 feet of the basic control on the levee and that vertical accuracy be maintained to at least 3rd order National accuracy standards (modified to an elevation accuracy of $\pm$ 0.15 feet absolute). Accuracy standards for most of this project were maintained. However, a section of about 10 miles of levee profile was not within specs. It has not been determined to date if this error was caused by bad basic control, misidentification of control or system malfunction. More details of this project are contained in a special report from the New Orleans District shown in the Appendix at the end of this report.

The last project was the establishment of horizontal and vertical coordinates for photogrammetric compilation of a flood plain map for Boone County, Missouri. This project was accomplished in one week using the RGSS of the US Army Engineer Topographic Laboratories. Elevation errors of less than 20 centimeters were obtained for all points established while running 240 kilometers of traverse. This project was done for the Kansas City District. The District Flood Plain manager stated that it would have taken a six-man team with 4 vehicles, 6 weeks using conventional surveying to accomplish the same work.

8. **SUMMARY OF OPERATIONAL RESULTS.** The United States Army Artillery anticipates a reduction of 15-30 percent in their survey personnel by using the Position and Azimuth Determining System (PADS), an inertial survey system that has been developed for military use. A total of 102 PADS are presently being built for the United States Army by Litton.

The Defense Mapping Agency (DMA) of the United States, has had a Litton inertial survey system in operation since 1975. The system has been used on 19 survey projects to establish 6,917 survey control points (most points required horizontal control of 3rd order or better accuracy as well as vertical control) over 60,680 kilometers of traversing. To accomplish the same amount of work using conventional surveying techniques would have required at least an additional 58 man years. In addition to being used for production, DMA's inertial system was on loan to USAETL for use in research and development programs in the use of inertial systems to measure the undulations in the earth's gravity field. DMA states that they consider their inertial system cost effective in that the payback period was slightly less than 2 years. DMA has also purchased a Honeywell inertial survey system but, at present, has little production experience using it.

The Bureau of Land Management (BLM) of the United States Department of the Interior has used inertial survey systems for land subdivision (horizontal control for the establishment of the exterior lines of townships) in Alaska since 1975. Personnel from the Anchorage office of BLM state that the system is very cost effective and has paid for itself in less than 2 years.

The Geodetic Survey of Canada, in operating an inertial system purchased from Litton in 1975, has realized savings from 40 percent to 50 percent on most of the projects on which the system was used to accomplish the work. The system has been used from the United States border to a latitude of 72° North and from the east coast to the west coast of Canada. The work accomplished with their inertial system includes the densification of geodetic control (horizontal and vertical) between primary control stations and the establishment of control for the Canadian 1:50,000 mapping program. The Canadians feel that the system paid for itself in less than 2 years.

SPAN, Inc., a commercial company located in Scottsdale, Arizona, has been using inertial survey systems since 1975. During this period, SPAN has been under contract to various U.S. and foreign Government agencies as well as U.S. and foreign corporations to perform surveys for basic control, mapping, construction, land data system, land subdivision, and geophysical purposes. SPAN started with a single system and has grown to a total of 5 systems. Since 1975, SPAN has traversed 255,706 kilometers and established control on 261,613 survey points. The work accomplished has met the accuracy requirements of the customers. When required the accuracy of the SPAN inertial system has met the United States standard for horizontal control Second Order, Class II.

In addition to SPAN Inc., three other commercial companies have entered the inertial field. These companies are: (1) Sheltech Canada, Calgary, Alberta, Canada, (2) International Technology Limited (ITECH), Anchorage, Alaska, and (3) World Surveys, Inc., Cape Canaveral, Florida. Sheltech developed and uses the Ferranti Inertial Land Surveyor (FILS), ITECH is also using the FILS but will soon be using the Litton Auto-Surveyor II; and World Surveys, Inc., will use the Honeywell GEO-SPIN. All of these companies will probably offer the same services as SPAN, Inc.

The United States Army Corps of Engineers has used inertial survey systems on five different projects located in the Portland, Huntington, Kansas City, Louisville and New Orleans Districts. The Portland District project was the largest of the five projects and consisted of two distinct tasks. The first task was establishing coordinates on the boundary corners of the John Day Dam and Reservoir. The second task was to establish control for the flood plain mapping project of Washington County, Oregon. It was estimated that the cost to accomplish both of these tasks would be approximately $260,000. SPAN did the job at a cost of $135,000 and completed both tasks in less than 45 days. Conventional surveying would have required at least 9 months to complete the same amount of work. The last project in which the Corp of Engineers used an inertial survey system was to obtain controlled profiles of levee crowns along the Mississippi River in the New Orleans District in early 1982. Since this was a rather unique use of an inertial survey system the after action report of the New Orleans District is shown in the appendix of this report.

9. **OPERATIONAL RECOMMENDATIONS.** All users of inertial surveyor systems have learned that there are advantages and disadvantages in using them. The most important thing is that it is costly and should be used only by individuals who thoroughly understand the equipment, its use, and its limitations. They must be very

adept at managing survey projects, much more so than survey projects done by conventional means. The system offers tremendous advantages. It can be operated in any weather, day or night. No manual reduction of field data is required. Unadjusted positional information is available immediately for field checks and the system can be used to recover existing control.

Some of the operational recommendations made by the users are:

(1) Field calibrate the system using first-order control only.

(2) Starting and ending stations for updates should be the highest order available. If the user wishes to establish second order control, use first - order control for update purposes.

(3) Run each traverse in the shortest time and distance possible.

(4) The more accurate the work desired, the less the time should be between ZUPTS.

(5) Have proper logistical support for the system including fuel caches for helicopters.

(6) Eliminate or reduce vibrations of the vehicle during ZUPTS (select proper idling speed in vehicle, keep vehicle engine properly tuned. If helicopter vibrates badly, place IMU on ground during ZUPTS).

(7) PLAN - PLAN, and PLAN.

V. ANALYSIS OF THE USE OF INERTIAL SURVEYING FOR CIVIL WORKS

1. **GENERAL.** The Survey Branches of three districts, New Orleans, Mobile and St. Louis, were visited to obtain information about the various types of survey projects at these districts. Information analyzed consisted of completed projects as well as projects still in the planning stages. New Orleans and Mobile were selected since they are in the two divisions that spend the greatest amount of money for surveying and mapping activities. Since OCE supports the Federal Emergency Management Administration, the Mobile District's efforts after Hurricane Frederick also were analyzed.

2. **NEW ORLEANS DISTRICT.** Over 380 requests for survey and data processing for a year were examined. These requests were dated from 1 October 1979 to 1 October 1980. Most of the requests were for survey work with a cost of under $20,000. It appears some of the small projects could have been combined into larger projects (the jobs were in neighboring areas or actually continuations of previous survey projects), so that inertial survey technology could have been used, resulting in savings to the Federal Government.

Table 6 lists a group of projects where an inertial survey system could have been used with at least a 20 percent savings over the actual cost of the conventional surveying techniques used.

The use of inertial survey technology for hydrographic surveying (boat-mounted) does not appear to be as cost effective as it is for other survey work. Current technology being used in the New Orleans District for hydrographic surveying is adequate.

3. **MOBILE DISTRICT.** The Mobile District has a few projects that will be very difficult to accomplish using conventional survey technology. These projects were examined in detail and are shown in Table 7. In addition to future projects, a flood plain mapping project of Slidell is also included in Table 7. The first four projects listed in Table 7 show an estimated cost of $780,000. It is estimated that these projects could be accomplished with an inertial survey system, at a cost between $500,000 and $600,000.

The Slidell, Louisiana Flood Plain Mapping Project was examined in detail. Based on the data examined, it appears that this project could have been completed at a cost under $120,000 if an inertial survey system had been used. Since this project is so well documented, it will probably be used as one of the inertial survey demonstration areas under OCE/Civil Works R&D Project 36131785.

4. **ST. LOUIS DISTRICT.** A basic control project has just been awarded to NGS by the St. Louis District to establish a unified net of horizontal and vertical control. The control on this project could be established with an inertial system. However, if vertical accuracies better than 0.1 of a foot are required, it would be difficult for an inertial survey system to meet this requirement. The personnel of the Survey Branch stated that though it was unfunded at the time, they would like to place coordinates

on all boundary corners of the reservoirs, recreation areas, and other Federal land under the jurisdiction of the District. This type of work is very easy for an inertial survey system to accomplish efficiently. Most of the other survey projects within this District are small and better accomplished using conventional survey techniques.

Table 6. New Orleans Survey Projects

PROJECT	LOCATION	COST
Mandeville Seawall Control Topo and Cross Section	Mandeville, LA	$46,500
Destrehan-Kenner Levee Enlargement Cross Sections and Control	Jefferson Parish	$97,500
Teche-Verimilion Horizonal & Vertical Control	St. Landry Parish	$23,000
Pontchartrain Level Enlargement Control and Cross Sections	St. John the Baptist Parish	$97,500
Control Tie of Survey Monuments	5th Louisiana Levee	$309,000 District
Control Mosic of Atchafalaya River Delta	Atchafalaya Bay	$30,000
Morganza Levee Enlargement Control	Atchafalaya River Basin	$84,000
Mississippi River Revetment Control Ties	Louisiana/Mississippi Border	$55,000
Gulf Intracoastal Waterway Waterway Control Survey	Cameron and Calcasied Parishes	$244,000

Table 7. Mobile District Survey Projects

PROJECT	COST	REMARKS
Luxapallila Creek Project	$200,000	Elevation good to 0.1 feet.
Third Order Control	$80,000	240 points over 60 miles.
Tom Bigbee Basic Control & Hydrographic Control	$400,000	150 miles of traverse with control better than 1 meter.
Alabama River Basic Control	$100,000	60 miles from junction with Tom Bigbee.
Flood Damage Study		Determine elevations of first floor on all existing structures in selected towns.
Pearl River Flood Plain Mapping of Slidell	$171,000	Already completed.

5. **FEDERAL EMERGENCY MANAGEMENT AGENCY.** Since many of the districts are responsible to give survey support for damage assessment after a disaster, such as hurricanes or floods, the support that the Mobile district gave FEMA, after Hurricane Frederick struck the Gulf Coast in the autumn of 1979, was examined. Contract survey crews were used since 6 survey parties were under open-end contracts. Difficulty in transporting and feeding those survey crews during the first month of work was the biggest problem. The final results of the survey work accomplished on Dauphin Island still has not been received because of difficulty with the basic control used to establish the control traverse. An inertial system mounted in a helicopter would have overcome most of the difficulties encountered in all of the work done for FEMA during this period and the results would have been in the hands of FEMA very shortly after the field work was completed (less than two weeks).

VI. CONCLUSIONS AND RECOMMENDATIONS

1. **CONCLUSIONS.** Inertial survey systems have proven themselves as extremely cost effective in accomplishing many types of geodetic and lower order control surveying. However, they do require a much higher level of planning than is presently required for conventional surveying. When properly used, a savings of 15 to 50 percent can be realized. The larger the job is, the greater the percentage of savings become.

Based on the analyses of work in some of the districts, OCE could realize savings in manpower and money if inertial survey technology was adopted by these districts. The savings would be rather small in the beginning, but as experience was gained in the use of inertial survey systems, the savings should be at least a 15 percent reduction in manpower and money presently required to support the survey requirements of the various districts.

Due to the speed which an inertial survey system obtains data, a central location for a system would be required. Based on the analyses done to date, it appears that if OCE obtains an inertial survey system, it should be based at a central location.

2. **RECOMMENDATIONS.** The Civil Works Directorate should initiate plans to purchase an inertial survey system. Since all companies using inertial survey systems will now do a total survey project rather than just leasing the equipment, they should be encouraged to actively compete for survey contracts where inertial surveying can meet the Corps requirements.

OCE/CIVIL Works Directorate should arrange to assist districts in preparing contracts for inertial surveys by using qualified personnel from their laboratories.

Studies or technical letters should be prepared for survey specifications for projects that require mapping, boundary or other survey control for Civil Works.

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APPENDIX

US ARMY COPRS OF ENGINEERS
NEW ORLEANS DISTRICT
SPECIAL REPORT

1. a. **Report title:** Inertial Surveying System

b. (1) Authors: Messrs Seale (Asst. Chief, Engineering Division) and Harrington (Chief, Design Services Branch).

(2) Contributors: Messrs Weiser (Chief, Survey Section) and Eames (of Survey) and Messrs Manson (Chief, Systems & Programming Section) and Flock (of Systems and Programming Section).

c. Date: 21 April 1982

2. **Description of work.**

a. Scope. The work consists of obtaining controlled profiles of the levee crowns within the New Orleans District. As a test, inertial survey methods were used to survey the West Bank of the Mississippi River from Black Hawk, LA (Northern Boundary of NOD) to the lower end of the Lafourche Basin Levee District which terminates approximately at the Mississippi River Bridge approximately 216.3 miles and on the East Bank within the Pontchartrain Levee District from the lower end of Bonnet Carre Spillway to the Orleans Parish line (approximately 23.7 miles). See Incl 1.

b. Need.

(1) A rapid method of obtaining accurate levee profiles is needed to know how many miles of levee are low relative to the authorized grade and where the low spots are located prior to flood fight activities within the New Orleans District. The short time requirements for making levee profiles led to a study to investigate state-of-the-art technology on advanced surveying methods. Inertial surveying methods seemed to offer the most promise.

(2) Profiles are used to help set priorities where deficiencies exist in the levee system.

c. Use. Survey data are used by Area Engineers and Sector Commanders in flood fight activities; by hydraulic and hydrologic engineers in flow and flowline determinations; and in establishing priorities of levee work.

3. **Requirements imposed by the Government.**

a. Vertical - Maintain or better the 3rd order accuracy presently being obtained from conventional methods (See Incl 2.). (It was verbally agreed that all profile elevations would be acceptable if they fell within 0.15 ft. absolute accuracy).

b. Horizontal - "Assure that the profile points are correlated with levee stationing to an accuracy of ± 5 feet". (See incl 2, page 43 of contract horizontal and vertical control and levee profiles).

c. Length of Survey - 240 miles.

d. Data Point Spacing -

(1) Every 100 ft. and all apparent grade changes (incl 3).

(2) Annotate all fences, cattle guards, ramps, utility crossings.

e. Contract start and completion date -

(1) Contract awarded 11/3/81.

(2) Notice to Proceed 11/25/81.

(3) Span's report, hard copy and nine-track tape delivered to COR 2/24/82.

(4) Data still being evaluated as of 4/19/82.

f. NOD's supervision and quality assurance. Several segments of the levees were profiled by conventional methods within 3 weeks after the inertial survey, to serve as "spot checks" (evaluation incomplete as of 4/19/82).

(1) Government furnished horizontal and vertical control.

g. Control requirements of the contractor. In order to provide the accuracy required by the government, the following arrangement was deemed necessary by the contractor:

(1) Vertical control - control had to be transferred from PBM's at the toe of the levee to 18" iron rods driven flush with the top of the levee crown. These marks had to be set every 3 miles throughout the 240 miles of profiles.

(2) Horizontal control monuments were uncovered, flagged and coded every 5 miles. (Points used were our 1976-77 levee marker survey monuments).

(3) Additional "Mile markers" (Iron Rods) were set each mile and tied in vertically and horizontally using the inertial system. These marks were double-run and "smoothed".

4. **Results of data collection.** The accuracy of the inertial survey system meets the requirements of the District. Difficulty was encountered in transferring the bench mark data from the toe-of-levee 2nd order vertical control to the levee crown control pins. This latter difficulty is a conventional survey method. Similary the major portion of the time was consumed in establishing control rather than running the profile with the inertial survey system.

5. **Comparison of survey methods.**

a. Time required.

(1) Inertial Survey

(a)	Synposis in CBD	13 Aug 80
(b)	Contract awarded	3 Nov 81
(c)	Conventional Survey Control began	7 Dec 81
(d)	Conventional Survey Control comp.	23 Dec 81
(e)	Inertial Survey began	6 Jan 82
(f)	Inertial Survey completed	13 Jan 82
(g)	Nine track tape received	24 Feb 82
(h)	Plats (182) completed	19 Feb 82

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Cal days

(2) Conventional Survey

			Calendar days
(a)	Begin Surveys	day 1	1
(b)	Complete Surveys	day 60	85
(c)	Checking Notes	day 80	112
(d)	Data Transcribing	day 85	
(e)	Plats (182)	day 100	140

b. Costs

(1) Inertial surveys

(a)	Contract	$98,231
(b)	Inhouse	2,271
		$100,502

(2) Conventional Surveys

(a)	Contract	$53,130
(b)	Inhouse S&A Survey	5,313
(c)	Inhouse	2,941
		$61,384

6. **Problems encountered.** The data for the 240 miles of profiles were forwarded to NOD on one 9 track magnetic tape. The majority of elevations were taken at 100 ft. intervals, although some were at distances of 2 to 3 feet and others at 150 to 300 feet. The data was recorded on tape as one record per point, which consisted of the following fields: latitude in seconds, longitude in seconds (signed negatively for West Hemisphere), state plane Northing coordinates (feet, Lambert conformal), state plane easting coordinates (feet, Lambert conformal) and reduced elevations in feet NGVD. The quality of the records written on the tape was overall good; however, the following items are noted and should be addressed in future contracts.

a. Several records on the tape were unreadable "spikes" or garbage records caused by end of file (EOF) markers on the cassette tapes which were used by Span International, Inc. to build the master tape.

b. Several records were truncated causing loss of data and uncreditibility.

c. Three or four areas on the tape indicated retrograde travel, e.g. recommencing at a point prior to the last record read. These areas were probably caused when the work stopped for the day and continued the following day.

d. The majority of the problems encountered on this project proved to be caused by errors made by the subcontractor during the layout phase of operations; especially in transferring elevations from the toe to the top of the levee using conventional leveling procedures. The layout phase, which was done by conventional methods was definitely a "weak link" on this project.

7. **Other pertinent or related information.**

a. Advantages - Disadvantages

Advantages over the conventional method.

(1) Surveys are not as restricted due to weather conditions.

(2) Data recorded directly on magnetic tape eliminates card punching from field books.

(3) Eliminates errors due to hand reducing notes and eliminates checking by survey personnel.

Disadvantages of the Inertial System.

(1) In areas where ruts existed on the levee, slight elevation errors occur.

(2) Inclosed areas such as shipyards, etc. when located on the levee make vehicle passage inaccessible resulting in conventional method to obtain these surveys.

(3) Notes such as size of pipes crossing the levee are hard to pick up.

(4) Potato ridges, or I walls can't be done by the system.

b. Computer program developed (To be used with either conventional or inertial surveys).

(1) In order to provide the profile data in a form traditionally used by NOD, (Plan Profile Maps) a recently developed Fortran program was modified. It was recognized it would be next to impossile for the draftpersons to plot elevations by Latitude and Longitude on State Plane coordinates in the time required. The program was written in FORTRAN IV for the DPS-1 computer at WES, and uses the CALCOMP plot routines. The runs are submitted for batch processing via timesharing and used the CARD subsystem.

(2) The program input was kept simple and consists of: title record, option record and the tape or disk files of stored data to be plotted. In this case NOD's latest 2nd order horizontal control was extracted from the computer data banks for the plan portion of the plot, and the 9 track tape provided by Span Int. for the vertical control on the profile portion of the plot. The horizontal control data was plotted in a true polyconic using routines which convert geodetic data to Universal Transverse Mercator and then to a polyconic coordinate system adapted for rotation of the plot.

(3) The vertical or profile data was plotted by converting the geodetic data to polyconic and incrementing from the first station on each map. Since this was NOD's first experience with inertial surveys, and also a study, the option to plot the data for the 182 plats on plain white paper instead of the aerial mosaic maps was made. This allowed NOD to overlay onto the existing plan profile maps containing the previous levee profiles for determination of the data integrity and accuracy. The output graphics were stored on magnetic tapes in the event the decision was made to plot the data directly on the aerial mosaics on the belt bed plotter for permanent records. The 182 plats were completed within 15 days utilizing one GS-7 engineering technician.

(4) Cost analysis for the Plats

a. Labor in obtaining the coordinates for each of the 182 mosaic maps. (Note this is a one time cost to NOD and would be required if the profiles were taken in a conventional way. Required for the new application for the belt bed plotter).

5 days at GS-7 = $306./182 = $1.68/sheet

(a) Computer method

(1) Job submittal for 182 plots

10 days at GS-7 = $612/182 = $3.36/sheet

(2) ADP Cost

5 minutes terminal time per sheet	$10.00/sheet
WES computer cost per sheet	9.50/sheet
	$19.50/sheet

(3) Programming cost (one time cost)

3 weeks at GS-12 = $1,846.9/182	= $10.14/sheet
First year cost/sheet	= 34.68/sheet
Subsequent year cost/sheet	= 22.86/sheet

(b) Manual Plot

Manual plot from previous contracts cost approximately	$178.00/sheet

8. **A-E Contract data.**

a. Method of procurement.

(1) Early actions.

(a) In Nov 79 the District Commander was approached by private industry about the possibility of using inertial surveys to accomplish part of our needs.

(b) Subsequently in Nov 79, Mr. Ken Robertson of ETL was contacted. Negotiations with ETL lasted until Mar 80 when we were informed that USAETL equipment would not be available. Another attempt was made with ETL but was suspended in Jul 80.

(c) In Aug 80 notice was issued in the Commerce Business Daily for firms to do the work as an indefinite quantities contract. Negotations on such a contract were terminated in Aug 81.

(2) Final actions. Negotiations on a fixed price contract began in Sep 81 and the contract was awarded in Nov 81. Initiation of work was delayed until Jan 82 because part of the levee was impassable due to temporary blockage of portions of the levee crown.

9. **Pertinent data on contractors.**

Maddox and Associates, Inc.
4701 Sangamore Road
Bethesda, Maryland 20016
301/229-3900
Contact: Tom Maddox, President

Professional Engineering Consultants
1646 Seabord Drive
Baton Rouge, Louisiana 70810
504/769-2810
Contacts: Larry McKee, Pres., P.E.C., Bill Gagnon

E. Jones & Associates, Inc.
2036 Wooddale Blvd. Suite "P"
Baton Rouge, Louisiana 70806
504/924-0540
Contact: Elmer Jones, President

Span International, Inc.
7330 Shoeman Lane
Scottsdale, Arizona 85251
602/994-3663
Contacts: Thomas F. Conlon, Jr., Rodger Campbell

10. **Discussions.**

a. The results presented herein suggest that inertial surveying offers a practical means for quickly obtaining profile information on levees, with a level of accuracy adequate for most uses. While the cost of obtaining the data on this occasion appear to be well in excess of those for obtaining the same information by conventional means, there is every indication that those costs can be significantly reduced, as will be discussed subsequently herein.

b. This effort was largely investigative and experimental in nature, hence it is to be expected that costs for actual production will be high. The contract involved a joint venture, which is not conducive to minimizing contract cost. The inertial equipment was mobilized from a distant location, and these costs will likely decline substantially as more and closer suppliers enter the field. This contract was negotiated under A-E procedures. If future procurements are made under competitive negotiations, an overall reduction can be expected.

c. The salient factor which resulted in high costs for this effort was the control layout work. It was necessary to establish 240 miles of temporary vertical control with monuments at 3-mile intervals, on the levee crown. The costs for this work represented one-third of the total contract cost, and the effort utilized 40% of the total contract time. We believe this area holds many possibilities for significant reduction. One method would be to permanently monument the levee crown, but this method would have a relatively high cost-about $200,000. In discussions with knowledgeable people in the field, however, we were told that the costs for establishing such control can be drastically reduced through the use of inertial surveying equipment installed in a helicopter. Under this arrangement, the vertical control would be transferred inertially from benchmarks located at the levee toe. This would also reduce the time involved drastically, perhaps to a week for the 240 miles of levees involved in this contract.

d. Beyond the problem of excessive time and cost for vertical control, inertial surveying of levees suffers from the fact that it would require acquisition under separate contract, while the conventional method requires only the issuance of a delivery order. This, however, is essentially a problem in administration which can be solved by altering administrative procedures. Several possibilities suggest themselves: We might enter into an open-ended contract for inertial surveys; or we might require inertial surveying capabilities, survey contracts, or permit the use of inertial surveying methods in our major surveying contracts. In any event, this problem is hardly insuperable.

e. It needs to be observed that the use of inertial surveying to produce profiles is not necessarily the use which is best suited to its potentials and advantages. Other uses appear to be even better suited to those potentials. Contour mapping in urban areas would be one task to which inertial surveying would be ideally suited.

f. In summary, we conclude that the use of inertial surveying has a distinct place in Corps work, even though there are some obvious problems --most notably with the time and costs for establishing the requisite vertical control--which need to be overcome. None of the problems that we encountered are, in our opinion, intractable. NOD plans to utililze inertial surveying for acquiring the next flood fight profiles needed. We believe that the costs will be comparable to those for conventional means and that there will be a great reduction in the time of acquisition.

11. **Recommendation**. It is recommended that all Corps offices be encouraged to increase their knowledge of inertial surveying and its potential in Corps work. It would probably be appropriate, as a catalyst, to arrange for seminars on inertial surveying in Division offices at an early date.

NOW, THEREFORE, the parties hereto do mutually agree as follows:

Article 1. Character and extent of services: The Contractor shall furnish the following work and services: perform profile surveys of 240 miles of Mississippi River levees utilizing inertial surveying technology. The technology must be keyed to minimize the turn around time required in taking the surveys, reduce cost, maintain or better the 3rd accuracy presently being obtained from conventional methods, edit the results, and compile the data into a format compatible for direct use in NOD's computer data system. The contractor shall furnish all professional engineering, technician, surveying management, and supervision support required to achieve the subject work. All labor, plant, software, hardware, transportation, fuel materials, and supplies necessary to accomplish the work shall be provided by the contractor.

The following levee reaches shall be surveyed:

Miss. River Right Bank Levees		Miss. River Left Bank Levees	
5th LA L.D.	0+00 (Black Hawk, LA)	Pont. L.D.	5269+69.65
" " "	886+60.57	" "	6519+94.65
AB L.D.	0+00		
	6223+32.42 = 0+00 LLD-A-LMS		
LLD-A-NO	0+00 LLD-A-LMS		
" "	4312+81.37		

Total Profile Mileage Right Bank	=	216.3 mi.
Total Profile Mileage Left Bank	=	23.7 mi.
TOTAL		240.0 mi.

The above surveys shall be accomplished in accordance with the Technical Provisions of this contract.

Article 2. Changes. (DAR 7-607.3--1972 APR)

(a) The Contracting Officer may, at any time, by written order, make changes within the general scope of the contract in the services to be performed. If such changes cause an increase or decrease in the contractor's cost of, or time required for, performance of any services under this contract, whether or not changed by any order, an equitable adjustment shall be made and the contract shall be modified in writing accordingly. Any claim of the contractor for adjustment under this clause must be asserted in writing within 30 days from the date of receipt by the contractor of the notification of change unless the Contracting Officer grants a further period of time before the date of final payment under the contract.

(b) No services for which an additional cost or fee will be charged by the contractor shall be furnished without the prior written authorization of the Contracting Officer.

TECHNICAL PROVISIONS

I. HORIZONTAL AND VERTICAL CONTROL

A. Horizontal Control. The Government has established a high-precision, monumented traverse (1976-1977 Levee Marker Survey Traverse) on top of the levees to be profiled. The P. I.'s of this traverse are located at each angle point in the levee on the levee crown, set approximately 0.5 ft. below the surface, and consist of Berntsen aluminum-magnesium, drive-in cone monuments containing permanent iron oxide magnets. Computer printouts of the traverse will be furnished the contractor and will contain such information as: station number of each monument, grid and geodetic azimuths of courses, latitude, longitude, and La. State Plane coordinates. It will be the responsibility of the contractor to locate a sufficient number of these monuments to assure that the profile points are correlated with levee stationing to an accuracy of ± 5 ft.

B. Vertical Control. The National Geodetic Survey has a line of first order levels along the levees to be profiled. The Permanent Bench Marks are located approximately every mile at the toe of the levees and are marked with witness posts and signs. It will be the responsibility of the contractor to locate and utililze these PBM's in whatever manner is deemed necessary to check and adjust the results of the inertial survey system. Copies of the descriptions, elevations, and scaled latitudes and longitudes of the PBM's will be furnished by the Government. The elevations are referred to the 1929 National Geodetic Vertical Datum.

II. LEVEE PROFILES

A. All points on the levee profile will be designated by station numbers from the 1976-77 Levee Marker Survey traverse. Station numbers shall be rounded off to the nearest foot in the final data output.

B. The contractor will be required to determine elevations along the levee crown every 100 feet and at all apparent grade changes.

C. All fences, cattle guards, ramps and utility crossings will be designated by station number and annotated according to the list of standard notations to be furnished to the contractor.

D. All final elevations will be output in tenths of a foot and will be based upon the latest available epoch of the 1929 National Geodetic Vertical Datum.

E. Complete and edited profile survey data for the levee reaches specified in Article 1 shall be furnished on computer printout (in accordance with the schedule required by Article 3) to the Contracting Officer Representative at 109 Research Drive, Harahan, LA 70123.